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MAGNITUDE:YIELD RELATIONSHIP AT VARIOUS NUCLEAR TEST SITES --- A MAXIMUM-LIKELIHOOD APPROACH USING HEAVILY CENSORED EXPLOSIVE YIELDS

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Conventional methods for estimating underground explosion yields from seismic recordings are based on the use of some appropriate "magnitude:yield" relationship. One of the most important parameters used to characterize the seismic signature of an underground explosion is the body-wave magnitude, m_b. Thus obtaining an unbiased measurement of m_b (or auxiliarily M_S, $Pcoda$, $m_b(L_g)$, M_o, and RMS L_g values) is obviously a key step in estimating the yield. During the past decade, the m_b which is averaged over a well-distributed global network and which incorporates the maximum-likelihood technique into the inversion scheme has become widely accepted as a means to obtain m_b estimates that avoid bias due to the detection threshold characteristics of individual network stations.

Recently Soviet seismologists have published descriptions of 96 nuclear explosions conducted from 1961 through 1972 at the Semipalatinsk Test Site, in Eastern Kazakhstan. With the exception of releasing news about their "peaceful nuclear explosions" [PNE], the Soviets have never before published such a body of information. However, out of the 72 Degelen events with announced yields, only 9 events or 12.5% were of "known" yields. The remaining were either left censored (66.7%) or bounded (20.8%). Similar heavy-censoring pattern can be found for other test sites. Thus the

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development of a procedure capable of making full use of such censored information would seem very timely and necessary .

In section I of this report, we present a maximum-likelihood regression scheme, "MLE-CY", which takes all the censored yields into account to refine the estimated m_b:yield relationship. This regression routine is very similar to the maximum-likelihood estimator used in computing the optimal network m_b values based on the censored station amplitude measurements due to clipping and to non-detection. In the non-censored case, it gives results identical to those derived by the standard least-squares method. Applications of this scheme to the explosions from several test sites of different geology show that it is a superior procedure, as compared to the conventional least-squares approach. The same algorithm can be applied to other magnitude measurements such as M_S, *Pcoda*, $m_b(L_g)$, M_o, RMS L_g and DOB *etc*.

We have also conducted a systematic analysis of the magnitude:yield relationship at five major test sites using miscellaneous **unclassified** magnitudes. (A **classified** annex using the official m_b values will be furnished separately.)

Several noteworthy results are summarized here:

[1] Including the censored yields in the regression does improve the accuracy of the estimates. In reality, both the magnitude and the yield measurements are subject to error. Pending the determination as to which of the two extreme hypotheses, namely $\sigma(m_b)/\sigma(Y) = 0$ and $\sigma(m_b)/\sigma(Y) = \infty$, is closer to the real situation, we also included the results based on Ericsson's method with various $\sigma(m_b)/\sigma(Y)$. As expected, we can see the smooth transition of estimated parameters (*i.e.*, the slope and the intercept) as $\sigma(m_b)/\sigma(Y)$ varies. Thus the censored cases with non-trivial $\sigma(m_b)/\sigma(Y)$ values could be "interpolated". Our maximum-likelihood regression scheme and Ericsson's method represent two different directions in extending the standard least squares.

[2] For Shagan events, Ringdal's *RMS* L_g provides the smallest scatter around the calibration curve, provided that low-yield events with $m_b(RMS\ L_g) < 5.5$ or yield < 40KT are excluded. Geotech's GLM method gives network m_b values better than almost all other magnitudes based on the teleseismic P waves and $\log(\Psi_\infty)$, in terms of both the yield estimation and the m_b scaling against Ringdal's *RMS* L_g. For all five test sites we have compared, m_b measurements reported by ISC and NEIS are biased high systematically at low yields.

[3] A direct estimation of the test site bias suggests that Nuttli's (1987, 1988) Degelen puzzle could be invalid simply because of the relatively poorer quality m_b(ISC) used. Our data indicate that Shagan River Test Site is more efficient in exciting teleseismic P waves than Degelen Mountain, consistent with our previous modeling study. Also, the test site bias is yield dependent, in agreement with other observational study.

[4] We present an alternative approach to derive the m_b adjustment converting cratering shots to contained explosions of the same yield. The correction derived by this approach seems to match that by the multichannel deconvolution method rather well.

[5] Degelen Mountain is the only test site that has a decreasing $\log(P_{max}/P_a)$ and $\log(P_b/P_a)$ with increasing yields. It is also the only test site for which the phase "a" (*i.e.*, zero-crossing to first peak) shows the smallest scatter around the calibration curve, as compared to the phases "b" (*i.e.*, first peak to first trough) and "max" (*i.e.*, max peak-to-trough or trough-to-peak in the first 5 seconds). Both the mountainous topography (which causes complex pP interference) as well as the testing practice (*e.g.*, the relatively shallow and abnormal shot depths) could be responsible. At Shagan River, the phase "b" has the smallest scatter around the calibration curve. These observations confirm the conjecture (DARPA, 1981) that in a proper environment the first cycle could give better results than does "max" phase.

[6] The scale depth for Konystan explosions is 146±1 meters, and the depth of burial [DOB] is roughly proportional to the quartic root of the yield, rather than the cubic root as frequently cited at NTS. This empirical scaling rule is applicable to Shagan River region, but not Degelen Mountain. For Konystan and Shagan regions, the yields estimated using depth scaling have accuracy comparable to those using m_b.

EXECUTIVE SUMMARY

Conventional methods for estimating underground explosion yields from seismic recordings are based on the use of some appropriate "magnitude:yield" relationship. One of the most important parameters used to characterize the seismic signature of an underground explosion is the body-wave magnitude, m_b. Thus obtaining an unbiased measurement of m_b (or auxiliarily M_S, *P*coda, $m_b(L_g)$, M_o, and RMS L_g values) is obviously a key step in estimating the yield. During the past decade, the m_b which is averaged over a well-distributed global network and which incorporates the maximum-likelihood technique into the inversion scheme has become widely accepted as a means to obtain m_b estimates that avoid bias due to the detection threshold characteristics of individual network stations.

Recently Soviet seismologists have published descriptions of 96 nuclear explosions conducted from 1961 through 1972 at the Semipalatinsk Test Site, in Eastern Kazakhstan. With the exception of releasing news about their "peaceful nuclear explosions" [PNE], the Soviets have never before published such a body of information. However, out of the 72 Degelen events with announced yields, only 9 events or 12.5% were of "known" yields. The remaining were either left censored (66.7%) or bounded (20.8%). Similar heavy-censoring pattern can be found for other test sites. Thus the development of a procedure capable of making full use of such censored information would seem very timely and necessary.

In section I of this report, we present a maximum-likelihood regression scheme, "MLECY", which takes all the censored yields into account to refine the estimated m_b:yield relationship. This regression routine is very similar to the maximum-likelihood estimator used in computing the optimal network m_b values based on the censored station amplitude measurements due to clipping and to non-detection. In the non-censored case, it gives results identical to those derived by the standard least-squares method. Applications of this scheme to the explosions from several test sites of different geology show that it is a superior procedure, as compared to the conventional least-squares approach. The same algorithm can be applied to other magnitude measurements such as M_S, *P*coda, $m_b(L_g)$, M_o, RMS L_g and DOB *etc.*

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the smooth transition of estimated parameters (*i.e.*, the slope and the intercept) as $\sigma(m_b)/\sigma(Y)$ varies. Thus the censored cases with nontrivial $\sigma(m_b)/\sigma(Y)$ values could be "interpolated". Our maximum-likelihood regression scheme and Ericsson's method represent two different directions in extending the standard least squares.

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SECTION I

MAXIMUM-LIKELIHOOD MAGNITUDE:YIELD REGRESSION WITH CENSORED INFORMATION

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I.0 ABSTRACT

Officially announced yields of underground nuclear explosions are often truncated or incomplete. So far such censored information has not been fully utilized in the determination of m_b:yield calibration curves. In this study, we present a maximum-likelihood regression scheme which takes all the censored yields into account to refine the empirical m_b:yield relationship. Preliminary applications of this scheme to the explosions from several test sites of different geology show that it is a superior procedure, as compared to the conventional least-squares approach. A joint and direct inversion reveals that the m_b bias between Eastern Kazakhstan, U.S.S.R., and Nevada Test Site, U.S., is about 0.40 and 0.44 at 10KT and 100KT, respectively. The same algorithm can be applied to other magnitude measurements such as M_S, Pcoda, $m_b(L_g)$, M_o and RMS L_g values *etc.*

I.1 INTRODUCTION

Conventional methods for estimating underground explosion yields from seismic recordings are based on the use of some appropriate "magnitude:yield" relationship. One of the most important parameters used to characterize the seismic signature of an underground explosion is the body-wave magnitude, m_b. Thus obtaining an unbiased measurement of m_b (or similarly M_S, Pcoda, $m_b(L_g)$, M_o, or RMS L_g values *etc.*) is obviously a key step in estimating the yield. There are already many publications which describe different procedures to infer better estimates of m_b: *e.g.*, Douglas (1966), von Seggern (1973), Ringdal (1976), von Seggern and Rivers (1978), Christoffersson and Ringdal (1981), Blandford and Shumway (1982), Blandford *et al.* (1983), Lilwall (1986), McLaughlin *et al.* (1988b), Lilwall *et al.* (1988), and most recently, Jih and Shumway (1989). During the past decade, the m_b which is

averaged over a well-distributed global network and which incorporates the maximum-likelihood technique into the inversion scheme has become widely accepted as a means to obtain m_b estimates that avoid bias due to the detection threshold characteristics of individual network stations.

Officially announced yields of underground nuclear explosions are often truncated or incomplete. In general there are four types of announced yields available:

[0] W is known as y_0 KT (*e.g.*, the Pahute Mesa event KNICKERBOCKER [5/26/67] had a yield of 71KT).

[1] W is left censored, *i.e.*, the exact value of W is known only to be less than a certain level t_1 (*e.g.*, the Konystan, U.S.S.R., event on [8/26/72] had a yield less than 20KT).

[2] W is right censored, *i.e.*, the exact value of W is known only to be larger than a certain level t_2 (*e.g.*, the Pahute Mesa event HANDLEY [3/26/70] had a yield slightly larger than 1000KT), and

[3] W is known only to lie between two bounds, t_a and t_b (*e.g.*, the Yucca Flat event FLASK [5/26/70] had a yield between 20 and 200KT).

Observations of types 1 through 3 are censored. Regression with right-censored data is an important topic in survival analysis as well as in quality control (Schmee and Hahn, 1979; Aitkin, 1981; and many others), while some biochemical and environmental studies involving the monitoring of toxic material or water quality have inevitably led to the analysis of left-censored data (*e.g.*, Gleit, 1985; Shumway *et al.*, 1989; and many others). Both left-censored and right-censored station recordings due to the ambient noise and signal clipping are crucial in the estimation of network m_b (Ringdal, 1976; von Seggern and Rivers, 1978; Blandford and Shumway, 1982; Jih and Shumway, 1989). For yield determination, likewise, neglecting any of the three aforementioned censoring patterns could cause serious bias, not to mention the waste of useful information. For instance, recently Soviet seismologists (Bocharov *et al.*, 1989) have published descriptions of 96 nuclear explosions conducted from 1961 through 1972 at the Semipalatinsk Test Site, in Eastern Kazakhstan (Vergino, 1989). With the exception of releasing news about their "peaceful nuclear explosions" [PNE] (Nordyke, 1974), the Soviets have never before published such a body of information. However, out of the 72 Degelen events with announced yields, only 9 events or 12.5% were of type 0. The remaining were either left censored (66.7%) or bounded (20.8%). The U.S. announced yields (Springer and Kinaman, 1971 and 1975) reflect a very similar heavy-censoring pattern. Although many authors have approached the subject of determining yield from m_b or other magnitude measures in a systematic way (*e.g.*, Evernden, 1967; Ericsson, 1971a, 1971b; Springer and Hannon, 1973; von Seggern, 1977; Dahlman and Israelson, 1977; Marshall *et al.*, 1979; Nuttli, 1986a, 1986b, 1988; Heasler *et al.*, 1988; *etc.*), the huge amount of censored information has never been fully utilized in the determination of m_b:yield calibration curves.

m_b:Yield Regression with Censored Data

In this study, we present a maximum-likelihood regression scheme which takes all the censored yields into account to refine the estimated m_b:yield relationship. This regression routine is very similar to the maximum-likelihood estimator used in computing the optimal network m_b values based on the censored station amplitude measurements due to clipping and to non-detection In the non-censored case, it gives identical results as that derived by the standard least-squares method. The same algorithm can be applied to other magnitude measurements such as M_S, Pcoda, $m_b(L_g)$, M_o and RMS L_g values *etc.*

I.2 MAXIMUM-LIKELIHOOD YIELD ESTIMATOR

The problem of estimating the yield of an explosion from the seismic magnitude has been handled traditionally using the linear model

$$X = \alpha + \beta \log(W) + v = \alpha + \beta Y + v \qquad [1]$$

where X is the measured magnitude, m_b, α and β are intercept and slope estimators, W is the yield in kiloton [KT], and v is an error term. v is assumed to be a Gaussian random variable with mean zero and standard deviation σ. The linear or piecewise-linear relationship between the log(yield) and the log(amplitude) is based on both observational study and theoretical prediction (*e.g.*, Mueller and Murphy, 1971; von Seggern and Blandford, 1972; Murphy, 1977).

One may then collect a number of "calibration events", estimating α and β by least squares using a number of known yields and measured magnitudes. This classical calibration approach leads to predicting a future log-yield Y at $m_b = \hat{X}$ by inverting equation [1], *i.e.*,

$$\hat{Y} = \frac{\hat{X} - \hat{\alpha}}{\hat{\beta}} \qquad [2]$$

The geometrical interpretation of "regressing X on Y" is that the $(\hat{\alpha}, \hat{\beta})$ thus estimated would be the optimal solution that minimizes the sum of the squared magnitude residuals, $\sum (X - \hat{\alpha} - \hat{\beta} Y)^2$ (and hence the name of "*m*-regression"). Implicitly, an assumption is been made that the independent variable Y has nearly perfect accuracy and precision as compared to X.

Alternately, one can estimate κ and λ in the inverse regression model

$$Y \equiv \log(W) = \kappa + \lambda X + v' \qquad [3]$$

and then predict a future log yield directly as

$$\hat{Y} = \hat{\kappa} + \hat{\lambda} \hat{X} \qquad [4]$$

Likewise, this so-called "*Y*-regression" approach implicitly assumes that X has perfect accuracy and precision. The optimal estimates $(\hat{\kappa}, \hat{\lambda})$ are the ones that would minimize the sum of the squared log yield residuals, $\sum (Y - \hat{\kappa} - \hat{\lambda} X)^2$. Thus either the yield or the magnitude must be regarded as error-free independent variable in these two models. In reality, both the m_b and the yield measurements are subject to error. At NTS, where the yields can be measured using the radiochemical method with a precision better than that of the seismic method, $\sigma(m_b) >> \sigma(\text{ log yield })$ could be a reasonable assumption. This may not be the case in general, however. Note that [3] can be rewritten in a form similar to [1]:

$$X = \alpha + \beta Y + v'' \qquad [3']$$

with the transformations $\alpha = -\kappa/\lambda$, $\beta = 1/\lambda$.

Now suppose there are n_0, n_1, n_2, and n_3 events for each type, respectively. We will derive the maximum-likelihood formulation for *Y*-regression model first (Equations [3] and [3']). The conditic..al likelihood function of the censored observations ($\mathbf{y}_0$, $\mathbf{t}_1$, $\mathbf{t}_2$, $\mathbf{t}_a$, $\mathbf{t}_b$) given the intercept α , slope β , and the standard deviation σ of error in log yield is

$$L(\mathbf{y}_0, \mathbf{t}_1, \mathbf{t}_2, \mathbf{t}_a, \mathbf{t}_b \mid \alpha, \beta, \sigma) = \prod_{j=1}^{n_0} P(Y_j = y_{0j} \mid \alpha, \beta, \sigma) * \prod_{j=1}^{n_1} P(Y_j < t_{1j} \mid \alpha, \beta, \sigma) *$$

$$\prod_{j=1}^{n_2} P(Y_j > t_{2j} \mid \alpha, \beta, \sigma) * \prod_{j=1}^{n_3} P(t_{aj} < Y_j < t_{bj} \mid \alpha, \beta, \sigma) \qquad [5]$$

and the log-likelihood function is

$$\ln L(\mathbf{y}_0, \mathbf{t}_1, \mathbf{t}_2, \mathbf{t}_a, \mathbf{t}_b \mid \alpha, \beta, \sigma) = -\frac{n_0}{2}\ln(2\pi\sigma^2) - \frac{1}{2\sigma^2}\sum_{j=1}^{n_0}(y_{0j} - \frac{x_{0j}-\alpha}{\beta})^2 +$$

$$\sum_{j=1}^{n_1}\ln \Phi(z_{1j}) + \sum_{j=1}^{n_2}\ln \Phi(-z_{2j}) + \sum_{j=1}^{n_3}\ln [\Phi(z_{bj}) - \Phi(z_{aj})] \qquad [6]$$

where x the seismic magnitudes; $z_i \equiv \dfrac{\alpha + \beta t_i - x_i}{\beta\sigma}$ for i = 1j, 2j, aj, and bj ; $\phi(u) \equiv \frac{1}{\sqrt{2\pi}}\exp(\frac{-u^2}{2})$ and $\Phi(u) \equiv \int_{-\infty}^{u}\phi(x)dx$ are the probability density function [p.d.f.] and the cumulative distribution function [c.d.f.] of the standard normal **N(0,1)**, respectively; and $\mathbf{y}_0$, $\mathbf{t}_1$, $\mathbf{t}_2$, $\mathbf{t}_a$, and $\mathbf{t}_b$ are the collection of announced yields. The specific form of the rightmost term in equation [6] reveals the necessity of treating the type 3 censored data as a separate class rather than considering each of type 3 event as two separate events of type 1 and 2.

Solving $\frac{\partial \ln L}{\partial \sigma} \equiv 0$ implies immediately that the maximum-likelihood solution of σ must satisfy the following necessary condition:

$$\sigma(\log \text{yield})^2 = \frac{\sum_{j=1}^{n_0}(y_{0j} - \frac{x_{0j}-\alpha}{\beta})^2}{n_0 + \sum_{j=1}^{n_1}\frac{\phi(z_{1j})}{\Phi(z_{1j})}z_{1j} - \sum_{j=1}^{n_2}\frac{\phi(z_{2j})}{\Phi(-z_{2j})}z_{2j} + \sum_{j=1}^{n_3}\frac{\phi(z_{bj})z_{bj} - \phi(z_{aj})z_{aj}}{\Phi(z_{bj}) - \Phi(z_{aj})}} \qquad [7]$$

(α, β, σ) can be solved iteratively with the Expectation Maximization (EM) algorithm (Dempster *et al.*, 1977) as follows:

- Initialization Step:

  Infer the initial guess of the unknown parameters, (α, β, σ), from the standard regression with the type 0 data alone.

- E Step:

  Replace the censored yields by their conditional expectations based on the current estimate of the parameters.

- M Step:

  Recompute σ with [7] and update α and β by regressing with the refined pseudo observations computed in the E step. Then repeat steps E and M until α, β, and σ converge.

Dempster *et al.* (1977) proved that such iterative procedure guarantees the monotonic increase of the likelihood function of the new estimate, which in turn guarantees the convergence of the whole procedure since the log-likelihood function defined in [6] is bounded above, say, by 0.

The following prerequisite mathematics are used in the E step. Let X be an arbitrary Gaussian random variable with mean μ and variance σ^2, p.d.f. g, c.d.f. G, then

- $E(X \mid X < a) = \mu - \sigma^2 g(a)/G(a)$,
- $E(X \mid X > a) = \mu + \sigma^2 g(a)/G(-a)$,
- $E(X \mid a < X < b) = \mu - \sigma^2 [g(b)-g(a)]/[G(b)-G(a)]$.

The calculation of g(x) and G(x) can be accomplished easily by the following transformations: $g(x) = \phi(\frac{x-\mu}{\sigma})/\sigma$, $G(x) = \Phi(\frac{x-\mu}{\sigma})$, as was done in Equations [6]-[7].

If we regress the magnitudes on the log yields, Equation [7] becomes

$$\sigma(m_b)^2 = \frac{\sum_{j=1}^{n_0}(\alpha + \beta y_{0j} - x_{0j})^2}{n_0 + \sum_{j=1}^{n_1} \frac{\phi(z_{1j})}{\Phi(z_{1j})} z_{1j} - \sum_{j=1}^{n_2} \frac{\phi(z_{2j})}{\Phi(-z_{2j})} z_{2j} + \sum_{j=1}^{n_3} \frac{\phi(z_{bj})z_{bj} - \phi(z_{aj})z_{aj}}{\Phi(z_{bj}) - \Phi(z_{aj})}} \qquad [8]$$

where $z_i \equiv \dfrac{\alpha + \beta t_i - x_i}{\sigma}$ for i = 1j, 2j, aj, and bj .

Essentially the same procedure can be used for both the *m*- and *Y*-regression models. The major difference in the M step is whether we regress Y on X (and then transform κ and λ to α and β) or regress X on Y to estimate α and β directly. The other minor difference is in the calculation of σ and z. The σ in [7] represents the standard deviation of the residual log yield, while the σ in [8] is actually that for the residual magnitude. For the *m*-regression model, $\sigma(m_b)$ in [8] is frequently used as a measure of goodness of fit. If the *Y*-regression model is used, $\sigma(m_b)$ can be computed as σ(log yield)*β. The 2σ uncertainty factor in yield is defined as 10**($2\sigma/\beta$) and 10**(2σ) for the *m*- and *Y*-regression models, respectively. Recently the *m*-regression model has been given greater attention in the nuclear monitoring study, and hence examples and discussions in the subsequent sections will be limited to the *m*-regression model for brevity. If $n_1 = n_2 = n_3 = 0$, then both algorithms presented here

reduce to the standard least-squares method, and σ in [7] and [8] becomes the simple RMS residuals in the usual sense.

I.3 ILLUSTRATIVE EXAMPLES

During the past several years, WWSSN (World-Wide Standard Seismograph Network) m_b database measured at Teledyne Geotech (TG) has been gradually expanded to 124 events, totaling 366 usable "a", "b", and "max" event phases (Blandford and Shumway, 1982; Blandford *et al.*, 1983; McLaughlin *et al.*, 1988b; Jih and Shumway, 1989; Jih *et al.*, 1990a; 1990b). We have applied the maximum-likelihood network m_b estimator, GLM [General Linear Model] (Blandford and Shumway, 1982), to the complete data set consisting of 15,288 teleseismic magnitude measurements in the distance range from 20 degrees to 95 degrees at 127 stations to determine our best m_b values to date, which we denote as m_b(TG). The $m_b(P_{max}$,TG) and $m_b(P_b$,TG) of the events from the same test site are then fed to the maximum-likelihood m_b:yield regression scheme we just proposed to derive the optimal calibration curve. The resulting calibration curves are summarized as follow:

(#1) $m_b(P_{max}$,TG) = 3.747[±0.075] + 0.857[±0.034] log(W) for NTS shots in high-coupling media; σ = 0.091; 95% confidence factor = 1.630; *i.e.*, we are 95% confident that the actual yield lies in the range from Y_{est}/1.630 to Y_{est}*1.630. In this regression (n_0, n_1, n_2, n_3) = (9,2,1,2).[1]

(#2) $m_b(P_b$,TG) = 3.484[±0.089] + 0.866[±0.040] log(W) for NTS shots in high-coupling media; σ = 0.108; 95% confidence factor = 1.775. (n_0, n_1, n_2, n_3) = (9,2,1,2).

(#3) $m_b(P_{max}$,TG) = 3.659[±0.022] + 1.008[±0.018] log(W) for Sahara and NTS shots in granite; σ = 0.032; 95% confidence factor = 1.157; (n_0, n_1, n_2, n_3) = (4,6,1,0) (*cf.* Table 1).

(#4) $m_b(P_b$,TG) = 3.348[±0.028] + 1.040[±0.022] log(W) for Sahara and NTS shots in granite; σ = 0.037; 95% confidence factor = 1.178; (n_0, n_1, n_2, n_3) = (4,6,1,0) (*cf.* Table 1).

(#5) $m_b(P_{max}$,TG) = 4.110[±0.062] + 0.892[±0.039] log(W) at Eastern Kazakhstan; σ = 0.093; 95% confidence factor = 1.617. (n_0, n_1, n_2, n_3) = (13,3,0,5).

(#6) $m_b(P_b$,TG) = 3.837[±0.059] + 0.924[±0.037] log(W) at Eastern Kazakhstan; σ = 0.091; 95% confidence factor = 1.571. (n_0, n_1, n_2, n_3) = (13,3,0,5).

Although the formulae (#1) through (#6) are preliminary, there are a few observations worth noting. First, the slope in (#1) matches Murphy's (1977) theoretical prediction, 0.85,

[1] 9 events of type 0: BILBY, SHOAL, HANDCAR, REX, CHARTREUSE, PILEDRIVER, SCOTCH, BOXCAR, and BENHAM; 2 events of type 1: ALMENDRO and MAST; 1 event of type 2: HANDLEY; 2 events of type 3: CORDUROV and NASH. See Appendix (page 64) for the m_b values.

rather well. Secondly, putting the representative explosions from various test sites recorded at a global network (such as WWSSN) into a single GLM inversion not only yields a consistent set of station corrections for global use, but it also provides a **direct** estimate of the m_b bias between any two test sites of interest. For instance, the m_b bias between Eastern Kazakhstan and NTS can be estimated easily from (#1) and (#5) as 0.40 and 0.436 magnitude unit at 10KT and 100KT, respectively. This value is very close to that based on some indirect methods using P_n velocity or surface waves (Evernden and Marsh, 1987), and slightly larger than that in Der *et al.* (1985) and Stewart (1988). It includes the combined effects of the net bias due to the clustering of stations on the focal sphere (McLaughlin, 1988) as well as the difference of Q, coupling, and pP interferences between two test sites.

In deriving (#3) and (#4), we have supplemented the French explosions in Hoggar Massif, south Algeria, with U.S. shots PILEDRIVER and SHOAL detonated at Climax Stock, Nevada. The French Test Site is in the volcanic terrain, apparently in an incipient rift zone (Duclaux and Michaud, 1970; Schock *et al.*, 1972; Faure, 1972). The t^* of Hoggar Massif as estimated by Der *et al.* (1985) is 0.35 sec, which shows no significant difference in the attenuation from that of NTS (McLaughlin *et al.*, 1988a). There exists fair agreement between U.S. and French granite shots in the yield-scaled peak values of acceleration, velocity, and displacement (Heuze, 1983). On the other hand, although the Semipalatinsk Test Site of U.S.S.R. has hard-rock geology as well, it is inappropriate to include the Soviet events in the same regression with French explosions unless care is taken in advance to correct for the test site bias. Table 1 lists the regression results using the least-squares (LS) and the maximum-likelihood estimator (MLE) along with the announced yields of U.S. and French tests in granite taken from Bolt (1976) and Stimpson (1988). The yield estimates in column "MLE" of Table 1 are predicted by formulae (#3) and (#4), respectively. Although the network m_b values we use are not corrected for the pP interference as suggested in Marshall *et al.* (1979), they fit the theoretical scaling rather well. The slope of the m_b:yield curve for this region is nearly 1 for these low-yield tests, consistent with an earlier study by Blandford and Shumway (1982) using fewer events. Because of the nearly ideal fit, the MLE changes the yields only slightly as estimated by the standard least squares method in this particular case.

Table 1. Estimated Yield of French and U.S. Explosions in Granite

Event	Announced [KT]	$m_b(P_{max},TG)$	LS [KT]	MLE [KT]	$m_b(P_b,TG)$	LS [KT]	MLE [KT]
BERYL	>20.0	4.986	20.6	20.8	4.779	23.8	23.8
CORUNDON	<20.0	4.214	3.5	3.6	3.900	3.4	3.4
EMERAUDE	<20.0	4.569	7.9	8.0	4.263	7.6	7.6
GRENAT	<20.0	4.766	12.4	12.6	4.497	12.7	12.7
OPALE	<20.0	3.894	1.7	1.7	3.853	3.1	3.1
RUBIS	52.0	5.432	57.2	57.5	5.170	56.4	56.5
SAPHIR	120.0	5.720	110.7	111.1	5.468	109.2	109.2
TOURMALINE	<20.0	4.646	9.4	9.5	4.429	10.9	11.0
TURQUOISE	<20.0	4.223	3.6	3.6	3.942	3.7	3.7
SHOAL	12.2	4.739	11.7	11.8	4.455	11.6	11.6
PILEDRIVER	56.0	5.436	57.7	58.0	5.195	59.7	59.7

We have also derived the maximum-likelihood calibration curves using Nuttli's (1986a) $m_b(L_g)$ as well as Marshall's (1988) m_b values for NTS:

(#7) Marshall's m_b = 3.892[±0.105] + 0.833[±0.049] log(W) for high-coupling material at NTS; σ = 0.186; 95% confidence factor = 2.799. Note that the mean slope, 0.833, is very close to that in (#1). (n_0, n_1, n_2, n_3) = (19,13,1,27).

(#8) Nuttli's $m_b(L_g)$ = 4.402[±0.038] + 0.730[±0.018] log(W) for high-coupling material at NTS; σ = 0.086; 95% confidence factor = 1.717. (n_0, n_1, n_2, n_3) = (22,14,1,30).

(#9) Nuttli's $m_b(L_g)$ = 4.020[±0.038] + 0.841[±0.032] log(W) for low-coupling material at NTS; σ = 0.170; 95% confidence factor = 2.536. (n_0, n_1, n_2, n_3) = (14,41,0,24).

To illustrate the robustness of the present approach, we have tabulated below (Table 2) the best yield estimate of several often analyzed nuclear tests in hard rock computed using our formulae based on Marshall's, Nuttli's, and our magnitudes.

Table 2. Comparison of Yield Estimate of 3 Granite Shots

Events	RUBIS	SAPHIR	Kazakhstan 01/15/65
Announced Yield	52KT	120KT	100-150KT
Nordyke*1	—	—	125KT
Dahlman and Israelson*2	—	—	110KT
Marshall *et al.**3	45.4KT [m_Q=5.97]	91.6KT [m_Q=6.29]	68.9KT [m_Q=6.16]
Nuttli*4 $m_b(L_g)$, Quadratic Fit Nuttli*5 $m_b(L_g)$, Linear Fit	68KT 70KT [$m_b(L_g)$=5.72]	110KT 117KT [$m_b(L_g)$=5.89]	103KT 109KT [$m_b(L_g)$=5.87]
Stimpson*6	68KT [m_b=5.49]	127KT [m_b=5.70]	—
This Study, $m_b(P_{max}$,TG)	57.5KT [$m_b(P_{max})$=5.432]	111.1KT [$m_b(P_{max})$=5.720]	96.7KT [$m_b(P_{max})$=5.882]
This Study, $m_b(P_b$,TG)	56.5KT [$m_b(P_b)$=5.170]	109.2KT [$m_b(P_b)$=5.468]	112.9KT [$m_b(P_b)$=5.735]

*1) Nordyke (1974): based on the crater size.
*2) Dahlman and Israelson (1977): slope = 0.74.
*3) Marshall *et al.* (1979): m_Q = 4.23[±0.15] + 1.05[±0.06] log(W) for salt and granite
*4) Nuttli (1986a, b): $m_b(L_g)$ = 3.943 + 1.124 log(W) - 0.0829 $(\log(W))^2$ for 5.2 < $m_b(L_g)$ < 6.7
*5) Nuttli (1986a, b): $m_b(L_g)$ = 4.307 + 0.765 log(W) for 5.2 < $m_b(L_g)$ < 6.7
*6) Stimpson (1988): m_b = 4.08 + 0.77 log(W) for hard rock

Patton (1988), Ringdal and Marshall (1989), Hansen *et al.* (1989), and Ringdal and Hansen (1989) confirmed that the L_g phase is very promising for use in yield estimation, as originally proposed by Nuttli (1986a, 1986b). Table 2 indicates that the yields estimated by our MLE regression scheme using our m_b measurements have equally good or better accuracy as does $m_b(L_g)$. The improvements over other conventional regression schemes can be attributed to two factors:

[1] the maximum-likelihood magnitude:yield regression method presented in this study is superior to the conventional least-squares magnitude:yield regression, regardless of what magnitude is used; and

[2] Geotech's GLM method results in a smaller bias in the network m_b estimates.

To explore the validity of the first claim, we analyzed 7 events with announced yields from the Shagan River Test Site (*i.e.*, Balapan region) as listed in Table 3 using Marshall's

(1987) m_b measurements and those of Sykes and Ruggi (1989).

When the standard least-squares (LS) is applied to Marshall's m_b values of the four events with known yields, the predicted yield of event [01/15/65] is 87.9KT. Once the remaining events of censored yields are added into our maximum-likelihood regression, the estimate becomes 92.0KT. If Sykes' m_b values were used instead, the yield estimate would change from 91.2KT (LS) to 94.9KT (MLE). Both cases show an obvious improvement relative to the announced yields by incorporating the censored yields into the regression. Furthermore, such improvement is not an isolated case. Out of 4 events with known yield, 3 events had significantly improved estimates.

Table 3. Explosions at Shagan River Area with Announced Yield

Date	Lat	Long	Depth	Yield	NEIS	Sykes	Marshall
	[N]	[E]	[m]	[KT]	m_b	m_b	m_b
650115	49.9350	79.0094	178	100-150	6.3	5.905	5.931
680619	49.9803	78.9855	316	<20	5.5	5.350	5.354
691130	49.9243	78.9558	472	125	6.0	5.954	6.048
710630	49.9460	78.9805	217	<20	5.4	5.290	5.027
720210	50.0243	78.8781	295	16	5.5	5.370	5.370
721102	49.9270	78.8173	521	165	6.2	6.181	6.224
721210	50.0270	78.9956	478	140	6.0	5.989	5.996

[from Bocharov *et al.* (1989) and Vergino (1989)]

The maximum-likelihood calibration curves at Shagan River region using m_b values in Table 3 ($(n_0, n_1, n_2, n_3) = (4,2,0,1)$) are listed as follow:

(#10)

Marshall's $m_b = 4.476[\pm 0.090] + 0.741[\pm 0.052] \log(W)$ with 95% confidence factor 1.605 and σ 0.076.

(#11)

Sykes' $m_b = 4.525[\pm 0.096] + 0.698[\pm 0.054] \log(W)$ with 95% confidence factor 1.577 and σ 0.069.

(#12)

NEIS' $m_b = 4.807[\pm 0.164] + 0.614[\pm 0.093] \log(W)$ with 95% confidence factor 2.671 and σ 0.131.

Bocharov *et al.* (1989) and Vergino (1989) also listed the yields of Soviet nuclear explosions in Konystan (Murzhik) and Degelen regions. Using Marshall's m_b measurements, the

maximum-likelihood calibration curves are:

(#13)

Marshall's m_b = 4.535[±0.045] + 0.768[±0.039] log(W) at Konystan; σ = 0.069; 95% confidence factor = 1.516. (n_0, n_1, n_2, n_3) = (6,7,0,1).

(#14)

Marshall's m_b = 4.370[±0.020] + 0.869[±0.017] log(W) at Degelen with σ 0.076 and 95% confidence factor 1.494. (n_0, n_1, n_2, n_3) = (9,46,0,15).

It remains to examine the second claim we made earlier, namely that the m_b values computed with Geotech's GLM method are better than those computed with other methods. We have separately regressed Marshall's (1988) and our m_b on the announced yields of the high-coupling shots detonated at NTS, using the same maximum-likelihood regression scheme. The results in Table 4 clearly indicate that for each event in common, our predicted yield is systematically closer to the announced yield than that based on Marshall's m_b values. About half of Geotech's NTS events in common with Nuttli's have the announced yields closer to the predictions based on our formula derived with Nuttli's $m_b(L_g)$, in accordance with Nuttli's claim that $m_b(L_g)$ could provide yield estimates as good as those based on the "good" m_b.

Table 4. Comparison of NTS Yield Estimates					
Date	Event Code	Announced W	Estimated W		
		[KT]	$m_b(L_g)$	m_b(Marshall)	$m_b(P_{max}$, TG)
621005	MISSISSIPPI	110	87.8	__	__
630913	BILBY	235	205.8	__	171.5
631026	SHOAL	12.2	12.0	__	14.4
641105	HANDCAR	12	7.3	7.5	10.7
660224	REX	16	16.0	8.3	13.7
660414	DURYEA	65	53.0	28.0	__
660506	CHARTREUSE	70	72.6	44.6	56.5
660527	DISCUSTHROWER	21	14.5	11.9	__
660602	PILEDRIVER	56	93.5	113.9	93.7
660630	HALFBEAK	300	351.9	412.1	__
661220	GREELEY	825	727.2	644.9	__
670520	COMMODORE	250	175.7	229.3	__
670523	SCOTCH	150	199.4	131.5	146
670526	KNICKERBOCKER	71	70.4	51.5	__
680426	BOXCAR	1200	1096	825	1293
681219	BENHAM	1100	1205	899	1122
691029	CALABASH	110	106.1	113.0	__
700526b	FLASK	105	99.6	98.9	__
701217	CARPETBAG	220	240.9	183.3	__
701218	BANEBERRY	10	12.8	21.9	__
710708	MINIATA	80	124.2	82.4	__
730426	STARWORT	85	96.5	100.0	__
# of Events			22+14+1+30	19+13+1+27	9+2+1+2
$\hat{\sigma}_{MLE}(m_b)$			0.086	0.186	0.091
2σ Factor			1.717	2.799	1.630

$\hat{W}(m_b(L_g))$ estimated with the formula #8.
$\hat{W}(m_b$,Marshall) estimated with the formula #7.
$\hat{W}(m_b$,TG) estimated with the formula #1.

m_b:Yield Regression with Censored Data

Patton (1988) repeated Nuttli's (1986a) procedure to estimate the yields of 69 NTS high-coupling shots recorded at LLNL's high-quality digital network. Based on his regression result, the predicted $m_b(L_g)$ at explosive yields of 10, 50, 100, 150KT are 5.159, 5.687, 5.914, and 6.047, respectively. Nuttli's (1986a) original regression with 22 NTS shots recorded at WWSSN stations gave 5.072, 5.607, 5.837, and 5.972, respectively (*cf.* formula *5 in Table 2). Our formula (#8), which is based on Nuttli's (1986a) $m_b(L_g)$ measurements exclusively, gives 5.132, 5.642, 5.861, and 5.990 at 10, 50, 100, and 150KT, respectively. It is obvious that our maximum-likelihood scheme gives $m_b(L_g)$ estimates closer to Patton's results at all levels of explosive yield. In other words, including the censored information in the regression as proposed in this study does improve the determination of the calibration curve, regardless of what type of magnitude is used.

I.4 DISCUSSION AND CONCLUSIONS

Officially announced yields of underground nuclear explosions are often truncated or incomplete. In this study, we have presented a maximum-likelihood regression scheme which takes all the censored yields into account to refine the estimated m_b:yield relationship with an attempt to make the maximum use of the available data. Preliminary applications of this scheme to events from several test sites of different geology show that it is indeed a superior procedure, as compared to the conventional least-squares approach. The same algorithm can be applied to other magnitude measurements such as M_S, $m_b(L_g)$ or RMS L_g values *etc.*

Nuttli's L_g work (1986a, 1986b) proposed that careful analysis of L_g peak amplitude data from explosions could produce yield estimates nearly as accurate as the best teleseismic estimates. Based on the assumption that his $m_b(L_g)$:yield formulae are site independent, he obtained a m_b bias estimate (relative to NTS) of 0.35 and 0.54 at Shagan River and Degelen Mountain, respectively. The combination of these two values would seem to be consistent with our preliminary m_b bias estimates of 0.40 (10KT) and 0.435 (100KT) based on events from Eastern Kazakhstan including Shagan River and Degelen Mountain.

Our regression with Marshall's (1987) m_b values suggests that there is a m_b bias of 0.112 and 0.150 at Konystan and Degelen, respectively, relative to Shagan River for 100KT shots. At 150KT, the bias becomes 0.117 and 0.173, respectively. Marshall's m_b values generally have better quality than the ISC (International Seismological Centre, Newbury, U.K.) bulletin data which Nuttli (1987) used. Thus combining this m_b(Marshall) bias estimate with Nuttli's m_b - $m_b(L_g)$ offset, 0.23, would imply that there is a $m_b(L_g)$ bias of approximately 0.23 - 0.15 = 0.08 and 0.23 - 0.173 = 0.057 at 100KT and 150KT, respectively, between Shagan River and Degelen Mountain. Linear finite-difference calculations by Jih and McLaughlin (1988) and Jih *et al.* (1989) also suggest that there should be observable coupling variations

affecting L_g amplitude. We are currently expanding Geotech's m_b database to investigate such spatial variation among three subregions of Eastern Kazakhstan (Jih *et al.*, 1990a; 1990b). At any rate, our preliminary analysis using Nuttli's $m_b(L_g)$ values tends to suggest that the regionalized calibration curves should provide a better result. For instance, formulae (#8) and (#9) would give a better fit than the formula (*5) in Table 2 for NTS events. In principle, this should be true not just for $m_b(L_g)$ alone. Porting any empirical magnitude:yield calibration curve from one site to another could be unreliable in some cases. The difference between formula (#10) for Shagan River and formula (#14) for Degelen Mountain is an example.

Recent theoretical studies on L_g (Lilwall, 1988; Jih *et al.*, 1989; Frankel, 1989) seem to agree that in a medium where the velocity increases with depth a smaller and smaller focal sphere of pS will be trapped as depth increases, thus decreasing the L_g amplitude. Since the larger shots are buried more deeply, this would imply that in general the slope in $m_b(L_g)$:yield relationship would be less than that in the m_b:yield relationship, as indicated in formulae (#1) through (#9).

Special purpose magnitudes, like m_Q in Marshall *et al.* (1979) which include corrections for source depth and source region attenuation should be, in principle, superior to m_b for estimating the explosive yield. However, the present study has shown that this may not be the case (*cf.* Table 2). The success of the *pP* and t* corrections depends on the accuracy of the corrections. In our examples, the network m_b (or, $\overline{m}_2$ in Marshall *et al.*, 1979), which were only corrected for the instrument gain, geometrical spreading (Veith and Clawson, 1972) as well as the station terms, would give fairly good yield estimates. Finally, the results in Table 2 seem to indicate that the phase "b" (*i.e.*, the first peak to the first trough) of the teleseismic P wave could give the yield estimate equally well as does the phase "max". However, further investigation is necessary.

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SECTION II

MAGNITUDE:YIELD RELATIONSHIP AT VARIOUS TEST SITES

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II.1 SUMMARY

We have conducted a systematic analysis of the magnitude:yield relationship at several test sites using miscellaneous magnitudes. The main tool of this study is a linear-regression scheme "MLE-CY" (Jih *et al.*, 1990a; 1990b) which takes all censored yields (*e.g.*, yield < 20 KT or 100 KT < yield < 150 KT) into account to refine the determination of the calibration curve. The majority of the recently published 96 Soviet explosive yields (Bocharov *et al.*, 1989; Vergino, 1989) and the U.S. announced yields (Springer and Kinaman, 1971, 1975) were heavily truncated or rounded, and hence the maximum-likelihood approach would seem ideal to make full use of the yield information. The regression routine we use is very similar to the maximum-likelihood estimator used in computing the optimal network m_b values based on the censored station amplitude measurements due to clipping and to noise (Blandford and Shumway, 1982; Jih and Shumway, 1989). In the non-censored case, it gives results identical to those derived by the standard least squares, corresponding to the two extreme cases of Ericsson's (1971) curve-fitting method which puts different variances in both the independent and the dependent variables.

In the following sections, we will tabulate the maximum-likelihood m_b:yield calibration curves which symbolically correspond to $\sigma(m_b)/\sigma(Y) = 0$ and ∞, respectively. Several noteworthy results are summarized here:

[1] Including the censored yields in the regression does improve the accuracy of the estimates (*cf.* Tables 2C and 2D). In reality, both the magnitude and the yield measurements are subject to error. Pending the determination as to which of the two extreme hypotheses, namely $\sigma(m_b)/\sigma(Y) = 0$ and $\sigma(m_b)/\sigma(Y) = \infty$, is closer to the real situation, we also included the results based on Ericsson's method with various $\sigma(m_b)/\sigma(Y)$. As expected, we can see the smooth transition of estimated parameters (*i.e.*, the slope and the intercept) as $\sigma(m_b)/\sigma(Y)$ varies (*cf.* Tables 2A, 4A, 5C, 6C, and 7B). Thus the censored cases with nontrivial $\sigma(m_b)/\sigma(Y)$ values could be "interpolated". Our maximum-likelihood regression scheme and Ericsson's method represent two different directions in

extending the standard least squares. In the future, Efron's bootstrap (Efron, 1979; Efron and Tibshirani, 1985) or other resampling techniques could be incorporated into Ericsson's curve-fitting routine to estimate the confidence interval.

[2] For Shagan events, Ringdal's *RMS* L_g provides the smallest scatter around the calibration curve, provided that low-yield events with $m_b(RMS\ L_g) < 5.5$ or yield < 40KT (*e.g.* the explosion on 10 Feb 72) are excluded. Geotech's GLM method (Blandford and Shumway, 1982) gives network m_b values better than almost all other magnitudes based on teleseismic P waves and $\log(\Psi_\infty)$, in terms of both the yield estimation (*cf.* Tables 2B and 5C) and the m_b scaling against Ringdal's *RMS* L_g (*cf.* Tables 5F and 9A). For all five test sites we have compared, m_b measurements reported by ISC and NEIS are biased high systematically at low yields (*cf.* Tables 2C, 4D, 5E, and 5D).

[3] A direct estimation of the test site bias (*cf.* Tables 9A and 9B) suggests that Nuttli's (1987, 1988) Degelen puzzle could be invalid simply because of the relatively poorer quality m_b(ISC) used. Our data indicate that the Shagan River Test Site is more efficient in exciting teleseismic P waves than Degelen Mountain, consistent with our previous modeling study (Jih and McLaughlin, 1988). Also, the test site bias is yield dependent, in agreement with other observational study.

[4] We present an alternative approach to derive the m_b adjustment converting cratering shots to contained explosions of the same yield (*cf.* Tables 8A and 8B). The correction derived by this approach seems to match that by the multichannel deconvolution method (Der *et al.*, 1985) rather well.

[5] Degelen Mountain is the only test site that has a decreasing $\log(P_{max}/P_a)$ and $\log(P_b/P_a)$ with increasing yields (*cf.* Tables 6D, 8A, and 8B). It is also the only test site for which the phase "a" (*i.e.*, zero-crossing to first peak) shows the smallest scatter around the calibration curve, as compared to the phases "b" (*i.e.*, first peak to first trough) and "max" (*i.e.*, max peak-to-trough or trough-to-peak in the first 5 seconds). Both the mountainous topography (which causes complex pP interference) as well as the testing practice (*e.g.*, the relatively shallow and abnormal shot depths) could be responsible. At Shagan River, the phase "b" has the smallest scatter around the calibration curve (*cf.* Tables 5C and 5D). These observations confirm the conjecture (DARPA, 1981) that in a proper environment the first cycle could give better results than does "max" phase.

[6] The scale depth for Konystan explosions is 146±1 meters, and the depth of burial [DOB] is roughly proportional to the quartic root of the yield, rather than the cubic root as frequently cited at NTS (*cf.* Table 7B). This empirical scaling rule is applicable to Shagan River test site, but not Degelen Mountain. For Konystan and Shagan regions, the yields estimated using depth scaling have accuracy comparable to those using m_b.

II.2 NTS

Table 2A. m_b:Yield Relation of NTS High-Coupling Shots							
(Earlier Studies)							
# of Events[1]	Magnitude	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor[2]	Method
22+0+0+0	Nuttli (1986a)	?	0.765±0.027	4.307±0.067	___	___	LS
69+0+0+0	Patton (1988)	∞	0.755±0.022	4.404±0.048	0.098	1.818	LS
(This Study)							
# of Events	Magnitude	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
22+14+1+30	Nuttli, $m_b(L_g)$	0	0.761±0.033	4.336±0.193	0.116	2.019	MLE-CY
22+14+1+30	Nuttli, $m_b(L_g)$	∞	0.730±0.018	4.402±0.038	0.086	1.717	MLE-CY
19+13+1+29	ISC	0	0.787±0.067	4.006±0.379	0.190	3.036	MLE-CY
19+13+1+29	ISC	∞	0.693±0.035	4.199±0.074	0.136	2.475	MLE-CY
19+13+1+27	Marshall	0	0.982±0.062	3.581±0.351	0.210	2.672	MLE-CY
19+13+1+27	Marshall	∞	0.833±0.049	3.892±0.105	0.186	2.799	MLE-CY
9+2+1+2	TG, P_a	0	0.893±0.088	3.165±0.450	0.204	2.863	MLE-CY
9+2+1+2	TG, P_a	∞	0.835±0.065	3.283±0.147	0.175	2.632	MLE-CY
9+2+1+2	TG, P_b	0	0.887±0.052	3.441±0.279	0.124	1.901	MLE-CY
9+2+1+2	TG, P_b	∞	0.866±0.040	3.484±0.089	0.108	1.775	MLE-CY
9+2+1+2	TG, P_{max}	0	0.872±0.045	3.716±0.253	0.105	1.744	MLE-CY
9+2+1+2	TG, P_{max}	∞	0.857±0.034	3.747±0.075	0.091	1.630	MLE-CY
22+0+0+0	Nuttli, $m_b(L_g)$	0	0.760±0.040	4.340±0.232	0.082	1.646	LS
22+0+0+0	Nuttli, $m_b(L_g)$	0.1	0.759±___	4.342±___	___	___	Ericsson
22+0+0+0	Nuttli, $m_b(L_g)$	1	0.745±___	4.370±___	___	___	Ericsson
22+0+0+0	Nuttli, $m_b(L_g)$	5	0.737±___	4.385±___	___	___	Ericsson
22+0+0+0	Nuttli, $m_b(L_g)$	100	0.737±___	4.386±___	___	___	Ericsson
22+0+0+0	Nuttli, $m_b(L_g)$	∞	0.737±0.029	4.386±0.060	0.081	1.659	LS

1) # of "exact" yields, # of left-censored yields, # of right-censored yields, and # of bounded yields.

2) the multiplicative uncertainty factor in the yield [KT] at 95% confidence level.

Table 2A. m_b:Yield Relation of NTS High-Coupling Shots (Continued)

(This Studies)

# of Events	Magnitude	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
9+0+0+0	TG, P_{max}	0	0.870±0.052	3.719±0.284	0.098	1.684	LS
9+0+0+0	TG, P_{max}	0.1	0.869±___	3.720±___	___	___	Ericsson
9+0+0+0	TG, P_{max}	1	0.860±___	3.738±___	___	___	Ericsson
9+0+0+0	TG, P_{max}	5	0.854±___	3.750±___	___	___	Ericsson
9+0+0+0	TG, P_{max}	100	0.854±___	3.751±___	___	___	Ericsson
9+0+0+0	TG, P_{max}	∞	0.854±0.044	3.751±0.093	0.097	1.692	LS

For purposes of estimating explosion yields, the media are divided into three types: unsaturated material, *e.g.*, alluvium and dry tuff; water-saturated rock; and granite. The U.S. granite shots PILEDRIVER and SHOAL will be discussed in the next section again.

If we ignore the different corner frequencies between events of large and small yields, and put all high-coupling shots in one single regression, then both Geotech's $m_b(P_{max})$'s and Marshall's m_b give a slope matching Murphy's (1977) theoretical prediction, 0.85, rather well (*cf.* Table 2A).

At NTS, yields estimated from m_b alone have a random uncertainty factor of 1.45 at the 95% confidence (*i.e.*, 2σ) level, provided the best "official" m_b values are used (U.S. Congress/OTA, 1988). None of the magnitudes listed in Table 2A reaches such a precision. However, it is also clear that the m_b based on our P_{max} is relatively more precise than other unclassified m_b measurements. The phase "a" has much larger variance than the phase "max" at NTS, possibly because of the small amplitudes measured were near the noise.

Table 2B. Maximum-Likelihood Yield Estimates of NTS Shots					
Date	Event Code	Announced W	Estimated W		
		[KT]	$m_b(L_g)$	m_b(Marshall)	$m_b(P_{max}$, TG)
621005	MISSISSIPPI	110	87.8	—	—
630913	BILBY	235	205.8	—	171.5
631026	SHOAL	12.2	12.0	—	14.4
641105	HANDCAR	12	7.3	7.5	10.7
660224	REX	16	16.0	8.3	13.7
660414	DURYEA	65	53.0	28.0	—
660506	CHARTREUSE	70	72.6	44.6	56.5
660527	DISCUSTHROWER	21	14.5	11.9	—
660602	PILEDRIVER	56	93.5	113.9	93.7
660630	HALFBEAK	300	351.9	412.1	—
661220	GREELEY	825	727.2	644.9	—
670520	COMMODORE	250	175.7	229.3	—
670523	SCOTCH	150	199.4	131.5	146
670526	KNICKERBOCKER	71	70.4	51.5	—
680426	BOXCAR	1200	1096	825	1293
681219	BENHAM	1100	1205	899	1122
691029	CALABASH	110	106.1	113.0	—
700526b	FLASK	105	99.6	98.9	—
701217	CARPETBAG	220	240.9	183.3	—
701218	BANEBERRY	10	12.8	21.9	—
710708	MINIATA	80	124.2	82.4	—
730426	STARWORT	85	96.5	100.0	—
# of Events			22+14+1+30	19+13+1+27	9+2+1+2
$\hat{\sigma}_{MLE}(m_b)$			0.086	0.186	0.091
2σ Factor			1.717	2.799	1.630
ρ^*			0.990	0.942	0.994

* ρ: the correlation coefficient between the magnitudes and the log yields.

m_b-Yield Calibration Curves

For each event in common with Marshall's in Table 2B, the yield predicted with Geotech's $m_b(P_{max})$ is always closer to the announced value than that based on Marshall's m_b values. As noted in Jih *et al.* (1990a), this would strongly suggest that Geotech's m_b values have smaller systematic error, since the same regression methodology was used.

Patton (1988) utilized Nuttli's procedure to estimate the yields for 69 high-coupling shots at NTS. The NTS explosions Patton used were clustered around $m_b(L_g) \approx 5.8$. Beyond that level, the difference in yield estimates between Nuttli's and Patton's predictions are by no means negligible. For $m_b(L_g) = 6.0$, they predict the yield to be 163KT (N) and 130KT (P), respectively. At $m_b(L_g) = 6.5$, the predictions are 736KT (N) and 597KT (P), respectively.

Since Patton (1988) did not release the individual yields or $m_b(L_g)$ in his paper, we need an alternative approach to make the comparison. The data recorded at LLNL's regional digital network have quality better than those WWSSN film chips which Nuttli (1986a) read. It would seem reasonable to assume that the m_b predicted by Patton's regression is more accurate than Nuttli's. Table 2c below indicates that regressing Nuttli's $m_b(L_g)$ measurements against the censored yields with our maximum-likelihood scheme gives m_b estimates very close to Patton's results at all levels of explosive yield. In other words, including the censored information in the regression as proposed in Jih *et al.* (1990a, 1990b) does improve the determination of the calibration curves, regardless of what magnitude is used.

Table 2C. Expected magnitudes of NTS High-Coupling Explosions (Regressing the magnitudes on the yields)					
(Earlier Studies)					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
Nuttli[1]	22+0+0+0	5.072	5.607	5.837	5.972
Patton[2]	69+0+0+0	5.159	5.687	5.914	6.047
(This Study)					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
Nuttli[3]	22+0+0+0	5.123	5.638	5.860	5.989
Nuttli[4]	22+14+1+30	5.132	5.642	5.861	5.990
ISC	19+13+1+26	4.892	5.376	5.585	5.707
Marshall	19+13+1+27	4.725	5.307	5.558	5.704
TG, P_a	9+2+1+2	4.118	4.701	4.953	5.100
TG, P_b	9+2+1+2	4.350	4.955	5.216	5.368
TG, P_{max}	9+2+1+2	4.604	5.202	5.460	5.610

1) Nuttli (1986a): $m_b(L_g)$ = 4.307[±0.067] + 0.765[±0.027]log(W) for 5.2 < $m_b(L_g)$ < 6.7.
2) Patton (1988): $m_b(L_g)$ = 4.404[±0.048] + 0.755[±0.022]log(W) for 4.22 < $m_b(L_g)$ < 6.7.
3) Nuttli's $m_b(L_g)$ values regressed with the least square, $\sigma(m_b)/\sigma(Y) = \infty$ (*cf.* Table 2A).
4) Nuttli's $m_b(L_g)$ values regressed with MLE-CY, $\sigma(m_b)/\sigma(Y) = \infty$ (*cf.* Table 2A).

Table 2C raises a question as how to evaluate different calibration curves. Apparently the trade off between α and β should be taken into account. Judging on the slope, β, alone could be very misleading. For instance, in comparison with the 2 slopes which we obtained with Nuttli's $m_b(L_g)$ measurements, his original slope is closer to that of Patton's (*cf.* Table 2A), and yet our formulae actually predict the yields as well as the magnitudes closer to those of Patton's (Tables 2C and 2D).

Table 2D. Expected Yields [KT] of NTS High-Coupling Explosions				
(Earlier Studies)				
m_b:Y Curve	$m_b(L_g)=4.5$	$m_b(L_g)=5.0$	$m_b(L_g)=5.5$	$m_b(L_g)=6.0$
Nuttli[1]	1.8	8.1	36.3	163.3
Patton[2]	1.3	6.2	28.3	130.0
(This Study)				
m_b:Y Curve	$m_b(L_g)=4.5$	$m_b(L_g)=5.0$	$m_b(L_g)=5.5$	$m_b(L_g)=6.0$
Nuttli[3]	1.4	6.8	32.5	155.1
Nuttli[4]	1.4	6.6	32.0	154.9
m_b:Y Curve	$m_b=4.5$	$m_b=5.0$	$m_b=5.5$	$m_b=6.0$
Marshall	5.4	21.4	85.2	339.5
TG, P_{max}	7.6	29.0	111.3	426.4

1) Nuttli (1986a): $m_b(L_g) = 4.307[\pm0.067] + 0.765[\pm0.027]\log(W)$ for $5.2 < m_b(L_g) < 6.7$.
2) Patton (1988): $m_b(L_g) = 4.404[\pm0.048] + 0.755[\pm0.022]\log(W)$ for $4.22 < m_b(L_g) < 6.7$.
3) Nuttli's $m_b(L_g)$ values regressed with the least square (*cf.* Table 2A).
4) Nuttli's $m_b(L_g)$ values regressed with MLE-CY (*cf.* Table 2A).

Due to the different yield relationships for teleseismic P and L_g at NTS, the yield estimates at the same "magnitude" level are very different. We will compare the $m_b(P)$ - $m_b(L_g)$ offset of various test sites in a later section (*cf.* Table 9A).

In comparing with Nuttli's regression results, we noticed that his original formula (Equation 1 in Table 2C) seems not reproducible. His data set (*cf.* Nuttli, 1986a, page 2144) included the Pahute Mesa event HANDLEY which had a bounded yield of >1000KT. However, Nuttli seemed to have treated the yield as exactly 1000KT in his calculations (*cf.* Figures 7 and 9 of Nuttli, 1986a). Different symbols for the 2 granite events PILEDRIVER and SHOAL were used in his figures (*cf.* Nuttli, 1986a, pages 2145 and 2147). Also, Nuttli imposed a $m_b(L_g)$ range of applicability (from 5.2 to 6.7) on his calibration curve.

We have tested eight possible combinations with Nuttli's $m_b(L_g)$ measurements:

- including NTS granite events or not,
- limiting $m_b(L_g)$ to [5.2,6.7] or not,
- assuming HANDLEY was 1000KT or deleting HANDLEY from the regression.

None of the eight extra experiments could give an "exactly identical" formula to that given by Nuttli (1986a), even if the computer's "machine ε" is accounted for. It seems very likely that Nuttli was using the "Y-regression" models, *i.e.*, $\sigma(m_b)/\sigma(Y) = 0$, with some unspecified constraint on the data set. However, for all cases we have tested, the comparisons of MLE results (using Nuttli's data) against Patton's result confirmed consistently that including the censored data would improve the regression.

II.3 U.S. AND FRENCH SAHARA SHOTS IN GRANITE

Table 3A. m_b:Yield Relation of French Sahara and NTS Events in Granite*

# of Events	m_b	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
4+0+0+0	TG, P_a	0	0.875±0.056	3.365±0.270	0.035	1.203	LS
4+0+0+0	TG, P_a	∞	0.869±0.049	3.374±0.083	0.035	1.203	LS
4+0+0+0	TG, P_b	0	1.048±0.064	3.334±0.325	0.048	1.234	LS
4+0+0+0	TG, P_b	∞	1.040±0.066	3.348±0.113	0.048	1.235	LS
4+0+0+0	TG, P_{max}	0	1.011±0.058	3.657±0.310	0.042	1.211	LS
4+0+0+0	TG, P_{max}	∞	1.004±0.058	3.668±0.099	0.042	1.212	LS
4+4+1+0	TG, P_a	0	0.928±0.044	3.258±0.195	0.061	1.353	MLE-CY
4+4+1+0	TG, P_a	∞	0.905±0.036	3.296±0.048	0.056	1.328	MLE-CY
4+6+1+0	TG, P_b	0	1.049±0.020	3.334±0.092	0.035	1.169	MLE-CY
4+6+1+0	TG, P_b	∞	1.040±0.022	3.348±0.028	0.037	1.178	MLE-CY
4+6+1+0	TG, P_{max}	0	1.014±0.018	3.658±0.084	0.032	1.154	MLE-CY
4+6+1+0	TG, P_{max}	∞	1.008±0.018	3.659±0.022	0.032	1.157	MLE-CY

*) 2 NTS events in granite and 9 French Sahara explosions; no P_a for EMERAUDE and TURQUOISE.

Table 3B. Yield Estimates of French & U.S. Shots in Granite							
Event	Official W	$m_b(P_{max})$	LS	MLE	$m_b(P_b)$	LS	MLE
	[KT]		[KT]	[KT]		[KT]	[KT]
BERYL	>20.0	4.986	20.6	20.8	4.779	23.8	23.8
CORUNDON	<20.0	4.214	3.5	3.6	3.900	3.4	3.4
EMERAUDE	<20.0	4.569	7.9	8.0	4.263	7.6	7.6
GRENAT	<20.0	4.766	12.4	12.6	4.497	12.7	12.7
OPALE	<20.0	3.894	1.7	1.7	3.853	3.1	3.1
RUBIS	52.0	5.432	57.2	57.5	5.170	56.4	56.5
SAPHIR	120.0	5.720	110.7	111.1	5.468	109.2	109.2
TOURMALINE	<20.0	4.646	9.4	9.5	4.429	10.9	11.0
TURQUOISE	<20.0	4.223	3.6	3.6	3.942	3.7	3.7
SHOAL	12.2	4.739	11.7	11.8	4.455	11.6	11.6
PILEDRIVER	56.0	5.436	57.7	58.0	5.195	59.7	59.7
# of Events			4+0+0+0	4+6+1+0		4+0+0+0	4+6+1+0
$\hat{\sigma}_{MLE}(m_b)$			0.042	0.032		0.048	0.037
2σ Factor			1.212	1.157		1.235	1.178
ρ			0.997	0.999		0.996	0.999

Table 3C. Expected m_b of U.S. and French Shots in Granite					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
TG, P_a	4+4+1+0	4.201	4.833	5.106	5.265
TG, P_b	4+6+1+0	4.388	5.115	5.428	5.611
TG, P_{max}	4+6+1+0	4.668	5.372	5.675	5.853

II.4 EASTERN KAZAKHSTAN AREA

Table 4A. m_b:Yield Calibration Curve at Eastern Kazakhstan*

# of Events	m_b	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
19+55+0+17	ISC	0	0.715±0.029	4.532±0.156	0.105	1.972	MLE-CY
19+55+0+17	ISC	∞	0.687±0.014	4.570±0.018	0.076	1.660	MLE-CY
19+55+0+17	NEIS	0	0.745±0.039	4.607±0.213	0.157	2.639	MLE-CY
19+55+0+17	NEIS	∞	0.655±0.019	4.725±0.023	0.113	2.222	MLE-CY
19+55+0+17	Sykes	0	0.717±0.024	4.535±0.129	0.088	1.755	MLE-CY
19+55+0+17	Sykes	∞	0.696±0.012	4.563±0.015	0.063	1.520	MLE-CY
19+0+0+0	Marshall	0	0.823±0.050	4.419±0.279	0.098	1.728	LS
19+0+0+0	Marshall	0.1	0.822±___	4.420±___	___	___	Ericsson
19+0+0+0	Marshall	1	0.802±___	4.448±___	___	___	Ericsson
19+0+0+0	Marshall	5	0.791±___	4.466±___	___	___	Ericsson
19+0+0+0	Marshall	∞	0.789±0.039	4.466±0.060	0.096	1.748	LS
19+55+0+17	Marshall	0	0.798±0.025	4.462±0.133	0.109	1.872	MLE-CY
19+55+0+17	Marshall	∞	0.759±0.015	4.516±0.018	0.087	1.696	MLE-CY
12+3+0+5	TG, P_a	0	0.951±0.042	3.497±0.208	0.094	1.577	MLE-CY
12+3+0+5	TG, P_a	∞	0.926±0.037	3.537±0.059	0.088	1.552	MLE-CY
13+3+0+5	TG, P_b	0	0.951±0.042	3.795±0.220	0.096	1.594	MLE-CY
13+3+0+5	TG, P_b	∞	0.924±0.037	3.837±0.059	0.091	1.571	MLE-CY
13+3+0+5	TG, P_{max}	0	0.921±0.047	4.064±0.257	0.102	1.666	MLE-CY
13+3+0+5	TG, P_{max}	∞	0.892±0.039	4.110±0.062	0.093	1.617	MLE-CY

*) including Shagan River (Balapan), Konystan (Murzhik), and Degelen Mountain.

In Table 4A, we regressed all Eastern Kazakh explosions with announced yields (Bocharov *et al.*, 1989) against various m_b values of Marshall (1987), ISC, NEIS, and ours. Detailed descriptions of the explosions are listed in later sections according to the subregion they belong to.

Table 4B. Least-Squares Yield Estimates of E. Kazakh Shots						
Event, Region	Official W	ISC	NEIS	Sykes	Marshall	TG, P_{max}
	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]
651121, D	29.0	32.0	48.0	31.0	27.7	25.6
660213, D	125.0	159.6	188.5	155.8	185.1	159.0
660320, D	100.0	115.7	188.5	112.8	98.6	88.2
660507, D	4.0	2.4	1.6	2.3	2.2	2.8
670922, M	10.0	8.8	8.7	8.5	7.6	—
680929, D	60.0	60.8	48.0	59.1	58.5	50.1
690723, D	16.0	16.8	17.2	16.2	20.6	15.6
691130, S	125.0	115.7	95.2	97.2	100.9	121.2
691228, M	40.0	44.1	34.1	42.8	47.7	—
710425, D	90.0	83.9	67.6	92.9	109.5	69.5
710606, M	16.0	23.2	17.2	21.0	22.0	—
711009, M	12.0	12.2	12.2	12.5	14.0	—
711021, M	23.0	23.2	24.3	23.1	25.8	—
720210, S	16.0	16.8	17.2	14.7	14.0	22.1
720328, D	6.0	6.4	6.2	7.0	8.0	9.2
720816, D	8.0	4.6	6.2	6.8	6.4	7.6
720902, M	2.0	3.4	4.4	3.0	2.6	—
721102, S	165.0	159.6	188.5	202.4	168.6	207.6
721210, S	140.0	115.7	95.2	108.8	86.7	133.4
# of Events		19+0+0+0	19+0+0+0	19+0+0+0	19+0+0+0	13+0+0+0
$\hat{\sigma}_{MLE}(m_b)$		0.080	0.120	0.070	0.096	0.097
2σ Factor		1.669	2.278	1.570	1.748	1.638
ρ		0.983	0.957	0.987	0.980	0.984

D = Degelen, S = Shagan (Balapan), M = Murzhik (Konystan).

Table 4C. Maximum-Likelihood Yield Estimates of E. Kazakh Shots

Event, Region	Official W	ISC	NEIS	Sykes	Marshall	TG, P_{max}
	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]
651121, D	29.0	31.7	43.9	30.8	27.3	25.4
660213, D	125.0	169.5	179.1	160.8	196.8	162.9
660320, D	100.0	121.2	179.1	115.5	102.1	89.5
660507, D	4.0	2.2	1.3	2.2	1.9	2.7
670922, M	10.0	8.3	7.6	8.2	7.1	—
680929, D	60.0	62.0	43.9	59.6	59.3	50.4
690723, D	16.0	16.2	15.3	15.9	20.1	15.4
691130, S	125.0	121.2	88.6	99.2	104.7	123.6
691228, M	40.0	44.3	30.9	42.9	48.0	—
710425, D	90.0	86.7	62.4	94.8	113.9	70.2
710606, M	16.0	22.7	15.3	20.7	21.5	—
711009, M	12.0	11.6	10.7	12.2	13.4	—
711021, M	23.0	22.7	21.7	22.9	25.3	—
720210, S	16.0	16.2	15.3	14.4	13.4	21.9
720328, D	6.0	5.9	5.3	6.7	7.4	9.0
720816, D	8.0	4.2	5.3	6.5	6.0	7.4
720902, M	2.0	3.0	3.7	2.8	2.3	—
721102, S	165.0	169.5	179.1	210.2	178.5	213.6
721210, S	140.0	121.2	88.6	111.4	89.4	136.4
# of Events		19+55+0+17	19+55+0+17	19+55+0+17	19+55+0+17	13+3+0+5
$\hat{\sigma}_{MLE}(m_b)$		0.076	0.113	0.063	0.087	0.093
2σ Factor		1.660	2.222	1.520	1.696	1.617
ρ		0.993	0.985	0.996	0.994	0.988

D = Degelen, S = Shagan (Balapan), M = Murzhik (Konystan).

Table 4D. Expected m_b of Eastern Kazakhstan Explosions					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
ISC	19+55+0+17	5.256	5.736	5.943	6.064
NEIS	19+55+0+17	5.380	5.837	6.034	6.150
Sykes	19+55+0+17	5.260	5.747	5.956	6.079
Marshall	19+55+0+17	5.274	5.805	6.033	6.167
TG, P_a	12+3+0+5	4.462	5.109	5.388	5.551
TG, P_b	13+3+0+5	4.761	5.407	5.685	5.848
TG, P_{max}	13+3+5+4	5.003	5.626	5.895	6.052

II.5 SHAGAN RIVER TEST SITE

Table 5A. Nuclear Explosions at Shagan River (Balapan) Region					
Date	Lat	Long	Depth	Yield	Rock
	[N]	[E]	[m]	[KT]	
650115	49.9350	79.0094	178	100-150	Sa
680619	49.9803	78.9855	316	<20	Sa
691130	49.9243	78.9558	472	125	Co
710630	49.9460	78.9805	217	<20	Co
720210	50.0243	78.8781	295	16	Al
721102	49.9270	78.8173	521	165	Al
721210	50.0270	78.9956	478	140	TS

Sa = Sandstone, Al = Aleurolite (Siltstone),
Co = Conglomerate, TS = Tuffaceous Sandstone
[from Bocharov *et al.* (1989) and Vergino (1989)]

Table 5B. Reported m_b of Shagan River Explosions							
Date	ISC	NEIS	Sykes	Marshall	Stewart*	Stewart*	Stewart*
	m_b	m_b	m_b	m_b	m_b	$\log(\Psi_\infty)$	M_o
650115	5.8	6.3	5.905	5.931	5.96	3.87	15.80
680619	5.4	5.5	5.350	5.354	5.60	3.31	15.24
691130	6.0	6.0	5.954	6.048	6.14	4.00	15.93
710630	5.2	5.4	5.290	5.027	5.29	2.98	14.91
720210	5.4	5.5	5.370	5.370	5.58	3.22	15.15
721102	6.1	6.2	6.181	6.224	6.39	4.38	16.31
721210	6.0	6.0	5.989	5.996	6.06	4.38	16.31

*) Averaged over EKA, YKA, GBA, and WRA.

Table 5B. Reported m_b of Shagan River Explosions (Continued)						
Date	EKA	Nuttli	Ringdal	TG	TG	TG
	m_b	$m_b(L_g)$	$RMS\ L_g$	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$
650115	5.98	5.87	5.950*	5.495	5.734	5.882
680619	5.70	—	—	4.620	5.002	5.263
691130	6.30	—	6.043	5.380	5.770	5.977
710630	5.34	—	—	4.472	4.768	5.041
720210	5.58	5.55	5.4**	4.805	5.074	5.306
721102	6.41	6.04	6.118	5.592	5.940	6.189
721210	6.08	6.09	6.095	—	5.786	6.015
710425***	N/A	N/A	5.862	N/A	N/A	N/A

*) Inferred indirectly from Nuttli's $m_b(L_g)$ = 5.87 (Ringdal and Marshall, 1989).

**) Low SNR for L_g phase (see text).

***) A Degelen event used in Ringdal (1989).

Table 5C. Magnitude:Yield Calibration Curve at Shagan River Area							
# of Events	Magnitude	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
4+2+0+1	ISC	0	0.655±0.132	4.584±0.753	0.116	2.267	MLE-CY
4+2+0+1	ISC	∞	0.628±0.055	4.645±0.097	0.077	1.753	MLE-CY
4+2+0+1	NEIS	0	0.722±0.709	4.621±1.225	0.189	3.346	MLE-CY
4+2+0+1	NEIS	∞	0.614±0.093	4.807±0.131	0.131	2.671	MLE-CY
4+2+0+1	Sykes	0	0.720±0.105	4.481±0.600	0.095	1.833	MLE-CY
4+2+0+1	Sykes	∞	0.698±0.054	4.525±0.096	0.069	1.577	MLE-CY
4+0+0+0	Marshall	0	0.795±0.137	4.385±0.811	0.088	1.669	LS
4+0+0+0	Marshall	0.1	0.795±___	4.387±___	___	___	Ericsson
4+0+0+0	Marshall	1	0.777±___	4.420±___	___	___	Ericsson
4+0+0+0	Marshall	5	0.767±___	4.439±___	___	___	Ericsson
4+0+0+0	Marshall	∞	0.767±0.105	4.441±0.206	0.087	1.685	LS
4+2+0+1	Marshall	0	0.768±0.089	4.421±0.510	0.098	1.803	MLE-CY
4+2+0+1	Marshall	∞	0.741±0.052	4.476±0.090	0.076	1.606	MLE-CY
4+2+0+1	EKA, m_b	0	0.705±0.246	4.724±1.457	0.236	4.654	MLE-CY
4+2+0+1	EKA, m_b	∞	0.568±0.104	4.983±0.181	0.165	3.809	MLE-CY
4+2+0+1	Stewart, m_b	0	0.667±0.220	4.738±1.293	0.207	4.170	MLE-CY
4+2+0+1	Stewart, m_b	∞	0.570±0.087	4.926±0.152	0.138	3.044	MLE-CY
4+2+0+1	Stewart, $\log(\Psi_\infty)$	0	1.098±0.124	1.865±0.467	0.172	2.061	MLE-CY
4+2+0+1	Stewart, $\log(\Psi_\infty)$	∞	0.953±0.135	2.134±0.237	0.189	2.498	MLE-CY
4+2+0+1	Stewart, M_o	0	1.099±0.124	13.795±1.942	0.172	2.061	MLE-CY
4+2+0+1	Stewart, M_o	∞	0.953±0.135	14.064±0.237	0.189	2.497	MLE-CY
3+0+0+1	Nuttli, $m_b(L_g)$	0	0.587±0.346	4.742±2.035	0.160	3.516	MLE-CY
3+0+0+1	Nuttli, $m_b(L_g)$	∞	0.546±0.106	4.835±0.207	0.087	2.085	MLE-CY
4*+0+0+1	Ringdal, *RMS* L_g	0	1.075±0.123	3.768±0.741	0.026	1.119	MLE-CY
4*+0+0+1	Ringdal, *RMS* L_g	∞	1.025±0.134	3.873±0.281	0.027	1.130	MLE-CY

*) Degelen event 710425 was used instead of Shagan event 720210.

Table 5C. Magnitude:Yield Calibration Curve at Shagan River Area (Continued)							
# of Events	Magnitude	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
3+2+0+1	TG, P_a	0	0.759±0.075	3.873±0.382	0.082	1.640	MLE-CY
3+2+0+1	TG, P_a	∞	0.738±0.041	3.910±0.069	0.060	1.456	MLE-CY
4+2+0+1	TG, P_b	0	0.812±0.044	4.083±0.238	0.051	1.332	MLE-CY
4+2+0+1	TG, P_b	∞	0.803±0.028	4.101±0.050	0.041	1.264	MLE-CY
4+2+0+1	TG, P_{max}	0	0.811±0.074	4.298±0.422	0.082	1.593	MLE-CY
4+2+0+1	TG, P_{max}	∞	0.788±0.039	4.336±0.068	0.067	1.475	MLE-CY

m_b(NEIS) are biased high at low yields for Shagan explosions simply because NEIS averages the signals reported. Consequently their m_b vs. log(W) slope is underestimated, which in turn causes the yields of the high-yield explosions to be overestimated. The yields estimated by Geotech's P_b seem to have accuracy at least as good as that based on P_{max}.

In Tables 5B and 5C, Stewart's m_b, $\log(\Psi_\infty)$, and M_o are those which are averaged over four arrays: Eskdalemuir (EKA) Scotland, Yellowknife (YKA) Canada, Gauribidanur (GBA) India, and Warramunga (WRA) Australia. The scatter is slightly reduced as compared to that based on a single array EKA. Marshall's m_b values are based on the ISC bulletin recordings (Marshall, personal communication).

Apparently the *RMS* L_g averaged over the bandpassed multi-channel signals recorded at NORSAR fit the announced yields very well. However, more data may be needed to further quantify its performance (Ringdal and Hansen, 1989) (*cf.* Table 5D). If Shagan event 720210 (which had poor L_g SNR at NORSAR) is included, the results would show a slightly greater scatter (σ = 0.056 and 0.040 for cases 0 and ∞, respectively). In Tables 5C through 5E, we have excluded this event at Ringdal's suggestion (Ringdal, personal communication).

Zavadil and Eisenhauer conjectured that the first or "b" phase could replace the phase "max." However, these AFTAC researchers and many others did not find convincing evidence to support their argument (DARPA, 1981). It seems this conjecture could well be valid at least for Shagan River. Among the three phases we measured, the phase "b" has the smallest scatter (*cf.* Table 5C), and it gives the best yield estimates (*cf.* Table 5D). At NTS and Sahara, the phase "b" has precision much better than the phase "a". At Degelen Mountain, phase "a" shows the smallest scatter, possibly because phases "b" and "max" are severely contaminated by the scattering at the free-surface topography (*cf.* Table 6C).

Table 5D. Maximum-Likelihood Yield Estimates of Shagan Explosions							
Date & Official W	ISC	NEIS	Sykes	Marshall	Stewart m_b	$\log(\Psi_\infty)$	M_o
[KT]	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]
650115, 100-150	69.2	269.6	94.9	92.0	65.0	66.3	66.4
680619, <20	16.0	13.4	15.2	15.3	15.2	17.1	17.1
691130, 125	144.2	87.6	111.6	132.4	134.5	90.8	90.8
710630, <20	7.7	9.2	12.5	5.5	4.3	7.7	7.7
720210, 16	16.0	13.4	16.5	16.1	14.0	13.8	13.8
721102, 165	208.1	185.3	235.9	226.0	369.2	227.6	227.6
721210, 140	144.2	87.6	125.2	112.7	97.4	227.6	227.6
$\hat{\sigma}_{MLE}(m_b)$	0.077	0.131	0.069	0.076	0.138	0.189	0.189
2σ Factor	1.753	2.671	1.577	1.606	3.044	2.498	2.497
ρ	0.986	0.958	0.989	0.991	0.957	0.962	0.963

Table 5D. Maximum-Likelihood Yield Estimates of Shagan Explosions (Continued)							
Date & Official W	EKA	Nuttli*	Nuttli**	Ringdal***	P_a	P_b	P_{max}
[KT]	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]
650115, 100-150	56.9	109	78.8	106.3	140.6	108.2	89.3
680619, <20	18.3	—	—	—	9.2	13.3	14.6
691130, 125	208.5	—	—	131.0	98.2	119.9	117.8
710630, <20	4.2	—	—	—	5.8	6.8	7.6
720210, 16	11.2	42	16.5	—	16.3	16.3	16.6
721102, 165	325.8	183	161.5	155.0	190.3	195.3	218.9
721210, 140	85.4	212	199.4	147.2	—	125.6	131.7
$\hat{\sigma}_{MLE}(m_b)$	0.165	—	0.087	0.027	0.060	0.041	0.067
2σ Factor	3.809	—	2.085	1.130	1.456	1.264	1.475
ρ	0.939	—	0.965	0.979	0.996	0.998	0.994

*) Nuttli (1986b): $m_b(L_g) = 4.307[\pm 0.067] + 0.765[\pm 0.027]\log(W)$ for $5.2 < m_b(L_g) < 6.7$.

**) Nuttli's $m_b(L_g)$ regressed by our maximum-likelihood code.

***) Degelen event 710425 was used instead of Shagan event 720210.

In 1988 the United States and the Soviet Union signed a bilateral agreement whereby each country was permitted to monitor at close distance an underground nuclear explosion at the other's main test site. The Soviet JVE (Joint Verification Experiment) shot was detonated on September 14, 1988, near the southern edge of the Shagan River Test Site. The New York Times states that the American and Soviet on-site measurements are said to give yields of 115KT and 122KT, respectively, for the Soviet JVE explosions (Sykes and Ekstrom, 1989). NORSAR's *RMS* L_g measurement for this event was 5.969 (Ringdal and Marshall, 1989). Assuming that the actual yield was between 100 and 150KT, as suggested by P. G. Richards, the regression using NORSAR's *RMS* L_g data including this event would give an estimate of 111.2KT, which is very close to Sykes' 113KT based on the average of m_b and M_S (Sykes and Ekstrom, 1989). The $\sigma(m_b)$ and the 95% factor in yield associated with NORSAR's data reduce from 0.027 and 1.130 (*cf.* Table 5D) to 0.026 and 1.122, respectively.

Table 5E. Expected Magnitudes of Shagan Explosions

m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
ISC	4+2+0+1	5.273	5.711	5.900	6.011
NEIS	4+2+0+1	5.421	5.850	6.035	6.144
Sykes	4+2+0+1	5.223	5.711	5.921	6.044
Marshall	4+2+0+1	5.217	5.735	5.958	6.088
EKA, m_b	4+2+0+1	5.551	5.948	6.119	6.219
Stewart, m_b	4+2+0+1	5.496	5.895	6.067	6.167
Stewart, $\log(\Psi_\infty)$	4+2+0+1	3.087	3.753	4.040	4.208
Stewart, M_o	4+2+0+1	15.017	15.683	15.970	16.138
Nuttli, $m_b(L_g)$	3+0+0+1	5.381	5.762	5.926	6.023
Ringdal, *RMS* L_g	4+0+0+1	—	5.614	5.923	6.103
TG, P_a	3+2+0+1	4.648	5.164	5.386	5.516
TG, P_b	4+2+0+1	4.904	5.465	5.707	5.848
TG, P_{max}	4+2+0+1	5.133	5.684	5.922	6.062

In Table 5D, we have listed two sets of yield estimates based on Nuttli's (1986b) $m_b(L_g)$ measurements. Although Nuttli's $m_b(L_g)$ database for Shagan had only four events in common with that of Bocharov, it is clear that regressing the $m_b(L_g)$ (or m_b) on each test site

separately, whenever the data are available, would give better results than the global calibration curve as recommended by Nuttli.

Table 5E indicates that our $m_b(P_{max})$ matches Ringdal's *RMS* L_g very well (except at low yields). Note that $m_b(L_g)$ is defined to be equal to m_b in eastern North America, which has geology similar to Eastern Kazakhstan. Thus relative to $m_b(L_g)$ scaling, our $m_b(P_{max})$ seem to have the smallest bias, as compared to other m_b. We have also regressed various magnitudes on Ringdal's *RMS* L_g with slope fixed at 1 (Table 5F). As expected, our $m_b(P_b)$ and $m_b(P_{max})$ possess the strongest correlation, the smallest scatter around the fitted straight line, as well as the smallest standard error in the estimated intercept.

Table 5F. Various Magnitudes Versus Ringdal's *RMS* L_g for Shagan Events*

Magnitude	$\sigma(m_b)$	Intercept	ρ
ISC	0.068	-0.034±0.028	0.968
NEIS	0.143	0.066±0.058	0.840
Sykes	0.094	0.002±0.039	0.960
Marshall	0.112	0.030±0.050	0.926
EKA, m_b	0.136	0.149±0.068	0.907
Stewart, m_b	0.125	0.105±0.062	0.912
Stewart, $\log(\Psi_\infty)$	0.211	-1.951±0.106	0.955
Stewart, M_o	0.211	9.979±0.106	0.955
Nuttli, $m_b(L_g)$	0.085	-0.016±0.049	0.986
TG, P_a	0.077	-0.560±0.039	0.968
TG, P_b	0.058	-0.266±0.026	0.988
TG, P_{max}	0.064	-0.057±0.029	0.982

*) Regressed on *RMS* L_g with slope 1 and free intercept.

It should not be surprising that M_o and $\log(\Psi_\infty)$ reported by the four British arrays give identical slope, σ, ρ, and yield estimates *etc.* (Tables 5C, 5D, and 5F) since Stewart (1988) computed the seismic moment, M_o, as

$$M_o \equiv 4 \pi d V_p^2 \Psi_\infty$$

where d = 2.4 g/cc and V_p = 5.0 km/sec are the presumed density and the *P*-wave velocity of the source material.

II.6 DEGELEN MOUNTAIN

Table 6A. Nuclear Explosions at Degelen Mountainous Region

Date	Lat [N]	Long [E]	Depth [m]	Yield [KT]	Rock
611011	49.77272	77.99500	116	<20	Gr
620202	49.77747	78.00164	238	<20	Gr
640315	49.81597	78.07517	220	20-150	Gr
640516	49.80772	78.10197	253	20-150	Gr
640719	49.80908	78.09292	168	<20	Gr
641116	49.80872	78.13344	194	20-150	QP
650303	49.82472	78.05267	196	<20	Gr
650511	49.77022	77.99428	103	<20	Gr
650617	49.82836	78.06686	152	<20	Gr
650729	49.77972	77.99808	126	<20	Gr
650917	49.81158	78.14669	156	<20	QP
651008	49.82592	78.11144	204	<20	QP
651121	49.81919	78.06358	278	29	Gr
651224	49.80450	78.10667	213	<20	QP
660213	49.80894	78.12100	297	125	QP
660320	49.76164	78.02389	294	100	QP
660421	49.80967	78.10003	178	<20	Gr
660507	49.74286	78.10497	274	4	QP
660629	49.83442	78.07336	187	20-150	Gr
660721	49.73667	78.09703	170	<20	QP

Gr = Granite, QP = Quartz Porphyrite, Po = Porphyrite, QS = Quartz Syenite
[from Bocharov *et al.* (1989) and Vergino (1989)]

Table 6A. Nuclear Explosions at Degelen Mountainous Region (Continued)					
Date	Lat	Long	Depth	Yield	Rock
	[N]	[E]	[m]	[KT]	
660805	49.76431	78.04242	171	<20	Gr
660819	49.82708	78.10875	134	<20	QP
660907	49.82883	78.06375	117	<20	Gr
661019	49.74711	78.02053	185	20-150	Gr
661203	49.74689	78.03336	153	<20	Gr
670130	49.76744	77.99139	131	<20	QS
670226	49.74569	78.08231	241	20-150	QP
670325	49.75361	78.06300	152	<20	Gr
670420	49.74161	78.10542	225	20-150	QP
670528	49.75642	78.01689	262	<20	QP
670629	49.81669	78.04903	195	<20	Gr
670715	49.83592	78.11817	161	<20	QP
670804	49.76028	78.05550	160	<20	Gr
671017	49.78089	78.00383	181	20-150	Gr
671030	49.79436	78.00786	173	<20	Gr
671208	49.81714	78.16378	150	<20	QP
680107	49.75442	78.03094	237	<20	Gr
680424	49.84519	78.10322	127	<20	QP
680611	49.79300	78.14508	149	<20	QP
680712	49.75469	78.08994	172	<20	Gr
680820	49.82264	78.07447	208	<20	Gr
680905	49.74161	78.07558	162	<20	Gr
680929	49.81197	78.12194	290	60	QP
681109	49.80053	78.13911	125	<20	QP
681218	49.74594	78.09203	194	<20	Gr
690307	49.82147	78.06267	214	20-150	Gr

Gr = Granite, QP = Quartz Porphyrite, Po = Porphyrite, QS = Quartz Syenite
[from Bocharov *et al.* (1989) and Vergino (1989)]

Table 6A. Nuclear Explosions at Degelen Mountainous Region (Continued)

Date	Lat	Long	Depth	Yield	Rock
	[N]	[E]	[m]	[KT]	
690516	49.75942	78.07578	184	<20	Gr
690704	49.74603	78.11133	219	<20	QP
690723	49.81564	78.12961	175	16	QP
690911	49.77631	77.99669	190	<20	Gr
691001	49.78250	78.09831	144	<20	Gr
691229	49.73367	78.10225	86	<20	QP
700129	49.79558	78.12389	214	20-150	Po
700327	49.74781	77.99897	138	<20	Gr
700527	49.73131	78.09861	66	<20	QP
700628	49.80150	78.10681	332	20-150	Gr
700724	49.80972	78.12839	154	<20	QP
700906	49.75975	78.00539	212	<20	Gr
701217	49.74564	78.09917	193	<20	Gr
710322	49.79847	78.10897	283	20-150	Gr
710425	49.76853	78.03392	296	90	Gr
710525	49.80164	78.13883	132	<20	Gr
711129	49.74342	78.07850	203	<20	Gr
711215	49.82639	77.99731	115	<20	Gr
711230	49.76003	78.03714	249	20-150	Gr
720310	49.74531	78.11969	171	<20	QP
720328	49.73306	78.07569	124	6	QP
720607	49.82675	78.11547	208	20-150	QP
720706	49.73750	78.11006	81	<20	QP
720816	49.76547	78.05883	139	8	Gr
721210	49.81939	78.05822	264	20-150	Gr
721228	49.73919	78.10625	132	<20	QP

Gr = Granite, QP = Quartz Porphyrite, Po = Porphyrite, QS = Quartz Syenite
[from Bocharov *et al.* (1989) and Vergino (1989)]

Table 6B. Reported m_b of Degelen Mountain Explosions							
Date	ISC	NEIS	Sykes	Marshall	TG, P_a	TG, P_b	TG, P_{max}
	m_b	m_b	m_b	m_b	m_b	m_b	m_b
611011	—	—	—	—	—	—	—
620202	—	—	—	—	—	—	—
640315	5.6	5.6	5.600	5.563	—	—	—
640516	5.6	5.6	5.600	5.549	—	—	—
640719	5.4	5.5	5.400	5.433	—	—	—
641116	5.6	6.0	—	5.642	—	—	—
650303	5.5	5.6	5.500	5.443	—	—	—
650511	4.9	5.2	4.900	4.742	—	—	—
650617	5.2	5.4	5.200	5.244	—	—	—
650729	4.5	4.5	4.500	—	—	—	—
650917	5.2	5.6	5.200	5.219	—	—	—
651008	5.4	5.7	5.400	5.471	—	—	—
651121	5.6	5.8	5.600	5.605	4.877	5.154	5.364
651224	5.0	5.0	5.000	4.944	—	—	—
660213	6.1	6.2	6.100	6.256	5.642	5.892	6.084
660320	6.0	6.2	6.000	6.040	5.337	5.626	5.852
660421	5.3	5.4	5.300	5.370	—	—	—
660507	4.8	4.8	4.800	4.734	3.994	4.235	4.488
660629	5.6	5.6	5.600	5.508	—	—	—
660721	5.3	5.4	5.300	5.360	—	—	—
660805	5.4	5.5	5.400	5.390	—	—	—
660819	5.1	4.8	5.100	4.633	—	—	—
660907	4.8	4.7	4.800	4.661	—	—	—
661019	5.6	5.7	5.600	5.669	—	—	—
661203	4.8	4.8	4.800	4.600	—	—	—
670130	4.8	4.8	4.800	4.627	—	—	—
670226	6.0	6.0	6.000	6.034	5.355	5.599	5.823
670325	5.3	5.3	5.300	5.320	—	—	—

Table 6B. Reported m_b of Degelen Mountain Explosions (Continued)

Date	ISC	NEIS	Sykes	Marshall	TG, P_a	TG, P_b	TG, P_{max}
	m_b	m_b	m_b	m_b	m_b	m_b	m_b
670420	5.5	5.7	5.500	5.556	—	—	—
670528	5.4	5.4	5.400	5.464	—	—	—
670629	5.3	5.3	5.300	5.336	—	—	—
670715	5.4	5.4	5.400	5.387	—	—	—
670804	5.3	5.3	5.300	5.316	—	—	—
671017	5.6	5.7	5.600	5.629	—	—	—
671030	5.3	5.5	5.300	5.413	—	—	—
671208	5.4	5.4	5.400	5.314	—	—	—
680107	5.1	5.3	5.100	4.977	—	—	—
680424	5.0	5.0	5.000	4.911	—	—	—
680611	5.2	5.3	5.200	5.240	—	—	—
680712	5.3	5.4	5.300	5.169	—	—	—
680820	4.8	4.8	4.800	4.761	—	—	—
680905	5.4	5.5	5.400	5.439	—	—	—
680929	5.8	5.8	5.800	5.861	5.127	5.434	5.629
681109	4.9	4.9	4.900	4.751	—	—	—
681218	5.0	5.2	5.000	5.044	—	—	—
690307	5.6	5.5	5.600	5.664	—	—	—
690516	5.2	5.3	5.200	5.264	—	—	—
690704	5.2	5.3	5.200	5.241	—	—	—
690723	5.4	5.5	5.400	5.504	4.596	4.922	5.169
690911	5.0	5.0	5.000	4.910	3.977	4.236	4.578
691001	5.2	5.3	5.200	5.256	—	—	—
691229	5.1	4.6	5.100	4.217	—	—	—
700129	5.5	5.6	5.500	5.599	—	—	—
700327	5.0	5.2	5.000	4.929	—	—	—
700527	3.8	—	3.800	—	—	—	—
700628	5.7	5.9	5.700	5.870	—	—	—

Table 6B. Reported m_b of Degelen Mountain Explosions (Continued)

Date	ISC	NEIS	Sykes	Marshall	TG, P_a	TG, P_b	TG, P_{max}
	m_b	m_b	m_b	m_b	m_b	m_b	m_b
700724	5.3	5.3	5.300	5.337	—	—	—
700906	5.4	5.6	5.400	5.533	—	—	—
701217	5.4	5.5	5.400	5.433	—	—	—
710322	5.7	5.8	5.700	5.767	—	—	—
710425	5.9	5.9	5.940	6.076	5.301	5.568	5.758
710525	5.1	5.2	5.020	5.048	—	—	—
711129	5.4	5.5	5.440	5.462	—	—	—
711215	4.9	4.9	4.900	4.677	—	—	—
711230	5.7	5.8	5.780	5.838	4.984	5.349	5.526
720310	5.4	5.5	5.410	5.453	—	—	—
720328	5.1	5.2	5.140	5.177	4.353	4.728	4.961
720607	5.4	5.5	5.400	5.422	—	—	—
720706	4.4	4.4	4.420	4.275	—	—	—
720816	5.0	5.2	5.130	5.105	4.339	4.622	4.887
721210	5.6	5.7	5.600	5.715	4.977	5.355	5.534
721228	—	—	4.900	—	—	—	—

Table 6B indicates that for Degelen events, all other m_b's are systematically larger than ours by a Δm_b of approximately 0.2 to 0.3. The m_b offset is less significant for Shagan events (*cf.* Tables 6B and 5E), however. This is possibly due to the different focusing and defocusing patterns between Shagan-Europe and Degelen-Europe paths. In our WWSSN database, there were 8 and 10 European stations which detected the Shagan event 650115 (100-150KT) and Degelen event 710425 (90KT), respectively. The averaged m_b residuals of the European WWSSN stations for these two events are 0.07±0.133 and 0.122±0.057, respectively. Marshall's database has a heavy clustering of ISC stations in Europe, and hence the resulting m_b offset may just be reflecting the even more severe path focusing effects enhanced by the ISC clustering in the western Europe.

Table 6C. m_b:Yield Calibration Curve at Degelen Mountain

# of Events	m_b	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
9+46+0+15	ISC	0	0.833±0.022	4.362±0.114	0.069	1.466	MLE-CY
9+46+0+15	ISC	∞	0.809±0.015	4.392±0.018	0.058	1.392	MLE-CY
9+46+0+15	NEIS	0	0.861±0.036	4.445±0.195	0.129	1.997	MLE-CY
9+46+0+15	NEIS	∞	0.773±0.024	4.556±0.028	0.110	1.920	MLE-CY
9+46+0+15	Sykes	0	0.803±0.019	4.414±0.102	0.062	1.426	MLE-CY
9+46+0+15	Sykes	∞	0.786±0.012	4.438±0.015	0.051	1.345	MLE-CY
9+0+0+0	Marshall	0	0.912±0.067	4.300±0.377	0.097	1.635	LS
9+0+0+0	Marshall	0.1	0.912±___	4.300±___	___	___	Ericsson
9+0+0+0	Marshall	1	0.897±___	4.322±___	___	___	Ericsson
9+0+0+0	Marshall	5	0.885±___	4.338±___	___	___	Ericsson
9+0+0+0	Marshall	100	0.884±___	4.340±___	___	___	Ericsson
9+0+0+0	Marshall	∞	0.884±0.059	4.340±0.090	0.096	1.647	LS
9+46+0+15	Marshall	0	0.908±0.022	4.318±0.115	0.083	1.525	MLE-CY
9+46+0+15	Marshall	∞	0.869±0.017	4.370±0.020	0.076	1.494	MLE-CY
9+1+0+3	TG, P_a	0	0.981±0.048	3.449±0.226	0.087	1.505	MLE-CY
9+1+0+3	TG, P_a	∞	0.959±0.044	3.479±0.066	0.084	1.499	MLE-CY
9+1+0+3	TG, P_b	0	0.972±0.058	3.752±0.297	0.108	1.665	MLE-CY
9+1+0+3	TG, P_b	∞	0.939±0.052	3.798±0.079	0.103	1.654	MLE-CY
9+1+0+3	TG, P_{max}	0	0.931±0.062	4.033±0.333	0.108	1.709	MLE-CY
9+1+0+3	TG, P_{max}	∞	0.899±0.051	4.079±0.078	0.099	1.660	MLE-CY

Table 6D. Expected m_b of Degelen Explosions					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
ISC	9+46+0+15	5.201	5.767	6.010	6.153
NEIS	9+46+0+15	5.329	5.870	6.103	6.239
Sykes	9+46+0+15	5.223	5.772	6.009	6.147
Marshall	9+46+0+15	5.239	5.846	6.108	6.261
TG, P_a	9+1+0+2	4.438	5.108	5.397	5.566
TG, P_b	9+1+0+2	4.737	5.393	5.676	5.841
TG, P_{max}	9+1+0+2	4.978	5.606	5.876	6.034

II.7 KONYSTAN (MURZHIK) AREA

Table 7A. Explosions at Konystan (Murzhik) Region

Date	Lat	Long	Depth	Yield	Rock	ISC	NEIS	Sykes	Marshall
	[N]	[E]	[m]	[KT]		m_b	m_b	m_b	m_b
651014	49.9906	77.6357	048	1.1	Al	—	—	—	—
661218	49.9246	77.7472	427	20-150	Po	5.8	5.9	5.800	5.922
670916	49.9372	77.7281	230	<20	Sa	5.3	5.3	5.300	5.245
670922	49.9596	77.6911	229	10	Al	5.2	5.3	5.200	5.160
671122	49.9419	77.6868	227	<20	Al	4.8	—	4.800	4.410
681021	49.7279	78.4863	31	0.2	Ar	—	—	—	—
681112	49.7124	78.4613	31	0.2x3	Gs	—	—	—	—
690531	49.9503	77.6942	258	<20	Al	5.3	5.4	5.300	5.290
691228	49.9373	77.7142	388	46	Al	5.7	5.7	5.700	5.791
700721	49.9524	77.6729	225	<20	Sa	5.4	5.4	5.400	5.376
701104	49.9892	77.7624	249	<20	Po	5.4	5.4	5.400	5.439
710606	49.9754	77.6603	299	16	Al	5.5	5.5	5.480	5.526
710619	49.9690	77.6408	290	<20	Po	5.4	5.5	5.410	5.538
711009	49.9779	77.6414	237	12	Al	5.3	5.4	5.320	5.371
711021	49.9738	77.5973	324	23	Sa	5.5	5.6	5.510	5.580
720826	49.9820	77.7166	285	<20	Al	5.3	5.5	5.370	5.363
720902	49.9594	77.6409	185	2	Sa	4.9	5.1	4.880	4.788

Sa = Sandstone, Al = Aleurolite (Siltstone), Po = Porphyrite, Gs = Gritstone
[from Bocharov *et al.* (1989) and Vergino (1989)]

Table 7B. m_b:Yield Calibration Curve at Konystan Area							
# of Events	m_b	$\frac{\sigma(m_b)}{\sigma(Y)}$	Slope	Intercept	$\sigma(m_b)$	2σ Factor	Method
6+7+0+1	ISC	0	0.632±0.097	4.659±0.518	0.093	1.962	MLE-CY
6+7+0+1	ISC	∞	0.602±0.036	4.691±0.042	0.057	1.542	MLE-CY
6+7+0+1	NEIS	0	0.500±0.106	4.894±0.573	0.099	2.490	MLE-CY
6+7+0+1	NEIS	∞	0.472±0.023	4.920±0.027	0.046	1.562	MLE-CY
6+7+0+1	Sykes	0	0.638±0.080	4.650±0.426	0.077	1.740	MLE-CY
6+7+0+1	Sykes	∞	0.617±0.031	4.671±0.036	0.048	1.429	MLE-CY
6+0+0+0	Marshall	0	0.791±0.102	4.498±0.547	0.081	1.598	LS
6+0+0+0	Marshall	0.1	0.790±___	4.498±___	___	___	Ericsson
6+0+0+0	Marshall	1	0.772±___	4.519±___	___	___	Ericsson
6+0+0+0	Marshall	5	0.761±___	4.531±___	___	___	Ericsson
6+0+0+0	Marshall	100	0.760±___	4.532±___	___	___	Ericsson
6+0+0+0	Marshall	∞	0.760±0.077	4.532±0.091	0.079	1.613	LS
6+7+0+1	Marshall	0	0.806±0.065	4.495±0.347	0.089	1.666	MLE-CY
6+7+0+1	Marshall	∞	0.768±0.039	4.535±0.045	0.069	1.516	MLE-CY
6+7+0+1	DOB*	0	0.278±0.400	2.136±0.972	0.143	10.713	MLE-CY
6+7+0+1	DOB	∞	0.245±0.024	2.164±0.028	0.035	1.915	MLE-CY

*) Depth of Burial.

Our maximum-likelihood regression routine can be applied to estimate the depth scaling rule as well (Jih, 1990). The result in Table 7B indicates that the scale depth for Konystan explosions is 146±1 meters. Furthermore, The depth of burial [DOB] is proportional to the quartic root of the yield, rather than the cubic root as frequently cited at NTS (*e.g.*, Evernden and Marsh, 1987). For Konystan test site, the yields estimated using DOB seem to have accuracy comparable to m_b (Table 7C). This is not the case for Degelen region, however (Jih, 1990).

Table 7C. Maximum-Likelihood Yield Estimates of Konystan Explosions						
Date	Official W	ISC	NEIS	Sykes	Marshall	DOB
	[KT]	[KT]	[KT]	[KT]	[KT]	[KT]
661218	20-150	69.5	118.8	67.4	64.2	80.1
670916	<20	10.3	6.4	10.4	8.4	6.4
670922	10	7.0	6.4	7.2	6.5	6.3
671122	<20	1.5	0.6	1.6	0.7	6.1
690531	<20	10.3	10.4	10.4	9.6	10.2
691228	46	47.4	44.8	46.4	43.3	54.2
700721	<20	15.0	10.4	15.2	12.5	5.8
701104	<20	15.0	10.4	15.2	15.1	8.8
710606	16	22.1	16.9	20.4	19.6	18.7
710619	<20	15.0	16.9	15.7	20.3	16.5
711009	12	10.3	10.4	11.2	12.3	7.2
711021	23	22.1	27.5	22.8	23.0	25.9
720826	<20	10.3	16.9	13.6	12.0	15.4
720902	2.0	2.2	2.4	2.2	2.1	2.6
$\hat{\sigma}_{MLE}(m_b)$ or $\hat{\sigma}_{MLE}(DOB)$		0.057	0.046	0.048	0.069	0.035
2σ Factor		1.542	1.562	1.429	1.516	1.915
ρ		0.990	0.993	0.993	0.992	0.971

Table 7D. Expected m_b & DOB of Konystan Explosions					
m_b:Y Curve	# of Events	10KT	50KT	100KT	150KT
ISC	6+7+0+1	5.293	5.714	5.895	6.001
NEIS	6+7+0+1	5.392	5.723	5.865	5.948
Sykes	6+7+0+1	5.289	5.720	5.906	6.014
Marshall	6+7+0+1	5.302	5.839	6.070	6.205
DOB (meter)	6+7+0+1	257	380	451	498

II.8 CRATERING VERSUS NON_CRATERING EXPLOSIONS

Tables 8A and 8B list the $\Delta_1 m_b \equiv \hat{m}_b(P_{max})$ - $\hat{m}_b(P_a)$ and $\Delta_2 m_b \equiv \hat{m}_b(P_b)$ - $\hat{m}_b(P_a)$ at four different test sites. As the yield increases from 10KT to 150KT, the Δm_b decreases steadily, except at Degelen Mountain. This could be yet another indication that the D.O.B. at Degelen does not quite follow the depth scaling. Note that Sahara Test Site has the same trend as Shagan.

Table 8A. Expected $\hat{m}_b(P_{max})$ - $\hat{m}_b(P_a)$ At 4 Test Sites

Test Site	10KT	50KT	100KT	150KT
NTS	0.486	0.501	0.507	0.510
Sahara	0.467	0.539	0.569	0.588
KTS	0.541	0.517	0.507	0.501
Shagan River	0.485	0.520	0.536	0.546
Degelen	0.540	0.498	0.479	0.468

Table 8B. Expected $\hat{m}_b(P_b)$ - $\hat{m}_b(P_a)$ At 4 Test Sites

Test Site	10KT	50KT	100KT	150KT
NTS	0.232	0.254	0.263	0.268
Sahara	0.187	0.282	0.322	0.346
KTS	0.299	0.298	0.297	0.297
Shagan River	0.256	0.301	0.321	0.332
Degelen	0.299	0.285	0.279	0.275

McLaughlin *et al.* (1985) studied the ratio of the P_a phase and P_{max} phase of presumed Shagan River contained and cratering explosions by comparing the WWSSN station m_b's. The motivation was that the logarithm of amplitude ratio of P_{max}/P_a of event 650115 was significantly smaller than other presumed contained explosions in the vicinity. Assuming the phase P_a is unaffected by the influence of the non-linear free-surface interference, then an adjustment to the $m_b(P_{max})$ should be able to convert that to a contained explosion of the

same yield. McLaughlin *et al.* (1985) concluded that a correction between 0.17 and 0.27 is needed for this conversion, assuming a yield of 125KT.

Based on 46 Shagan River explosions recorded at EKA, Ringdal and Marshall (1989) derived a value of 0.75 as their mean $\log(P_{max}/P_a)$ across the EKA array using the same techniques as used in McLaughlin *et al.* (1985). The cratering event 650115 had $m_b(P_{max})$ - $m_b(P_a)$ = 0.62 at EKA, and hence they apply a correction of 5.87 + 0.75 - 0.62 = 6.00 for a hypothetical contained explosion with equivalent yield. Both Ringdal and Marshall (1989) and McLaughlin *et al.* (1985) have the same methodological drawback in that they did not take the yields of those reference contained explosions into account, due to the lack of data at the time.

We utilize the statistics in Tables 8A and 8B to illustrate that the correction by Ringdal and Marshall (1989) might be slightly more accurate than that in McLaughlin *et al.* (1985). In Table 8A, we have $\hat{m}_b(P_{max})$ - $\hat{m}_b(P_a)$ = 0.536 at 100KT, and 0.546 at 150KT. Since for event 650115 our $m_b(P_{max},\mathrm{TG})$ - $m_b(P_a,\mathrm{TG})$ = 0.387 (Table 5B), this would imply an adjustment of 0.149 (100KT) and 0.159 (150KT), and a corrected m_b of about 6.031 (100KT) and 6.041 (150KT), respectively. Note that the adjusted m_b at 150KT, 6.041, is almost identical to the "expected $m_b(P_{max})$" of 6.062 (*cf.* Table 5E). The corrected m_b at 100KT would match that of Ringdal's rather well if the standard error in the uncorrected $m_b(P_{max})$, 5.882±0.046, is taken into account.

Der *et al.* (1985) deconvolved four contained and the cratering Shagan events [650115] recorded at EKA, and then they convolved the Green's functions with an appropriate attenuation operator as well as the source-time function of various yields of interest. By comparing the phases P_a and P_{max} of the synthetics, they obtained a cratering-to-contained correction of 0.15, 0.15, and 0.18 at 60, 125, and 300KT, respectively. The match with our result is remarkably good. This approach would seem very attractive if the database can be expanded to events covering a wide range of yields (and hence depths) and then the method can be applied to events in the same yield range.

II.9 TEST SITE BIAS

Table 9A. Expected $\hat{m_b}(P)$ - $\hat{m_b}(L_g)$ at Various Test Sites

Test Site	Description	10KT	50KT	100KT	150KT
(Earlier Studies*)					
NTS	m_b(ISC) - Nuttli's $m_b(L_g)$	-0.31	-0.31	-0.31	-0.31
Shagan River	m_b(ISC) - Nuttli's $m_b(L_g)$	0.04	0.04	0.04	0.04
Degelen	m_b(ISC) - Nuttli's $m_b(L_g)$	0.27	0.27	0.27	0.27
Degelen	m_b(Sykes) - Nuttli's $m_b(L_g)$	0.23	0.23	0.23	0.23
Novaya Zemlya	m_b(ISC) - Nuttli's $m_b(L_g)$	-0.11	-0.11	-0.11	-0.11
(This Study)					
Test Site	Description	10KT	50KT	100KT	150KT
NTS	m_b(Marshall) - Patton's $m_b(L_g)$	-0.434	-0.380	-0.356	-0.343
NTS	$m_b(P_{max}$, TG) - Patton's $m_b(L_g)$	-0.555	-0.485	-0.454	-0.437
Shagan River	m_b(Marshall) - Ringdal's $RMS\ L_g$	—	0.121	0.035	-0.015
Shagan River	$m_b(P_{max}$, TG) - Ringdal's $RMS\ L_g$	—	0.070	-0.001	-0.041
Degelen	m_b(Marshall) - Ringdal's $RMS\ L_g$	—	0.232	0.185	0.158
Degelen	$m_b(P_{max}$, TG) - Ringdal's $RMS\ L_g$	—	-0.008	-0.047	-0.069

*) Nuttli (1987, 1988).

At Degelen and Shagan, our results show that the $m_b(P)$ - $m_b(L_g)$ has a decreasing tendency with increasing yield, contrary to the increasing trend at NTS. Results based on Marshall's m_b are consistent with ours.

Table 9B. Expected Test Site Bias

(Earlier Studies)

Test Sites	Description	10KT	50KT	100KT	150KT
Shagan - NTS	Nuttli (1987)	0.35	0.35	0.35	0.35
Degelen - NTS	Nuttli (1987)	0.54	0.54	0.54	0.54
Shagan - Degelen	Nuttli (1987)	-0.19	-0.19	-0.19	-0.19
Novaya Zemlya - NTS	Nuttli (1987)	0.20	0.20	0.20	0.20

(This Study)

Test Sites	Description	10KT	50KT	100KT	150KT
Ringdal's *RMS* L_g(Shagan) - $m_b(P_{max}$, TG, Sahara)		___	0.243	0.253	0.251
Ringdal's *RMS* L_g(Shagan) - $m_b(L_g)$ (Patton, NTS)		___	-0.073	0.009	0.056
KTS - NTS	m_b(Marshall)	0.549	0.498	0.475	0.463
KTS - NTS	$m_b(P_a$, TG)	0.344	0.408	0.435	0.451
KTS - NTS	$m_b(P_b$, TG)	0.411	0.452	0.469	0.480
KTS - NTS	$m_b(P_{max}$, TG)	0.399	0.424	0.435	0.442
Shagan - NTS	m_b(Marshall)	0.492	0.428	0.400	0.384
Shagan - NTS	$m_b(P_a$, TG)	0.530	0.463	0.433	0.416
Shagan - NTS	$m_b(P_b$, TG)	0.554	0.510	0.491	0.480
Shagan - NTS	$m_b(P_{max}$, TG)	0.529	0.482	0.462	0.452
Degelen - NTS	m_b(Marshall)	0.514	0.539	0.550	0.557
Degelen - NTS	$m_b(P_a$, TG)	0.320	0.407	0.444	0.466
Degelen - NTS	$m_b(P_b$, TG)	0.387	0.438	0.460	0.473
Degelen - NTS	$m_b(P_{max}$, TG)	0.374	0.404	0.416	0.424
Sahara - NTS	$m_b(P_a$, TG)	0.083	0.132	0.153	0.165
Sahara - NTS	$m_b(P_b$, TG)	0.038	0.160	0.212	0.243
Sahara - NTS	$m_b(P_{max}$, TG)	0.063	0.168	0.214	0.240
KTS - Sahara	$m_b(P_a$, TG)	0.261	0.276	0.282	0.286
KTS - Sahara	$m_b(P_b$, TG)	0.373	0.292	0.257	0.237
KTS - Sahara	$m_b(P_{max}$, TG)	0.335	0.254	0.220	0.199

Table 9B. Expected Test Site Bias (Continued)					
(This Study)					
Test Sites	Description	10KT	50KT	100KT	150KT
Shagan - Sahara	$m_b(P_a, \text{TG})$	0.447	0.331	0.280	0.251
Shagan - Sahara	$m_b(P_b, \text{TG})$	0.516	0.350	0.279	0.237
Shagan - Sahara	$m_b(P_{max}, \text{TG})$	0.465	0.312	0.247	0.209
Degelen - Sahara	$m_b(P_a, \text{TG})$	0.237	0.275	0.291	0.301
Degelen - Sahara	$m_b(P_b, \text{TG})$	0.349	0.278	0.248	0.230
Degelen - Sahara	$m_b(P_{max}, \text{TG})$	0.310	0.234	0.201	0.181
Shagan - Degelen	m_b(ISC)	0.072	-0.056	-0.110	-0.142
Shagan - Degelen	m_b(NEIS)	0.092	-0.020	-0.068	-0.095
Shagan - Degelen	m_b(Sykes)	0.000	-0.061	-0.088	-0.103
Shagan - Degelen	m_b(Marshall)	-0.022	-0.111	-0.150	-0.173
Shagan - Degelen	$m_b(P_a, \text{TG})$	0.210	0.056	-0.011	-0.050
Shagan - Degelen	$m_b(P_b, \text{TG})$	0.167	0.072	0.031	0.007
Shagan - Degelen	$m_b(P_{max}, \text{TG})$	0.155	0.078	0.046	0.028
Konystan - Degelen	m_b(ISC)	0.092	-0.053	-0.115	-0.152
Konystan - Degelen	m_b(NEIS)	0.063	-0.147	-0.238	-0.291
Konystan - Degelen	m_b(Sykes)	0.066	-0.052	-0.103	-0.133
Konystan - Degelen	m_b(Marshall)	0.063	-0.007	-0.038	-0.056
Konystan - Shagan	m_b(ISC)	0.020	0.003	-0.005	-0.010
Konystan - Shagan	m_b(NEIS)	-0.029	-0.127	-0.170	-0.196
Konystan - Shagan	m_b(Sykes)	0.066	0.009	-0.015	-0.030
Konystan - Shagan	m_b(Marshall)	0.085	0.104	0.112	0.117

The m_b bias between Sahara and Degelen is interesting in that different phases exhibit opposite tendency of bias change with yields. The bias determined with phase "a" increases with yields, while that of phases "b" and "max" decrease.

Based on Geotech's m_b:yield calibration curves, Shagan River would have more efficient P-wave coupling than does Degelen River by an offset of about 0.155 m.u. (magnitude unit)

and 0.046 m.u. at 10KT and 100KT, respectively. This m_b bias can be explained by the profound topography at Degelen Mountain which could cause strong P-to-S conversion, as illustrated by the linear finite-difference calculations (Jih and McLaughlin, 1988). The bias value currently used by the U.S. government is intended to be the most appropriate value for yields near the 150KT threshold of the 1974 Threshold Test Ban Treaty (TTBT). Our results in Table 9B provide a direct clues of how different the bias could be at lower yields.

A brief review of earlier work on test site bias may be interesting. Based on the P-wave seismograms of three granite explosions (PILEDRIVER, Shagan 680619, and Shagan 710630) recorded at EKA, Douglas (1987) concluded that the Shagan-NTS bias is about 0.5, which is very close to what we got with phases P_b and P_{max} (Table 9B). Stewart (1988) predicted a bias of 0.37 at m_b=5.0 and of 0.32 at m_b=6.5, based on the m_b averaged across four arrays: Eskdalemuir (EKA) Scotland, Yellowknife (YKA) Canada, Gauribidanur (GBA) India, and Warramunga (WRA) Australia. His predicted bias is yield-dependent, and it has a decreasing trend with increasing yield, which is consistent with our maximum-likelihood results in Table 9B. This tendency should not be surprising. Large-yield explosions generate predominantly low-frequency signals and low-yield explosions are relatively richer in higher frequencies, so a relatively large amount of energy is removed by the attenuation from low yield tests, hence the bias is greater for such low yield explosions. Furthermore, the bias between two sites is made up of more than just the attenuation in the mantle beneath the test site. A difference in depth containment laws and up-hole velocities between the test sites can have an effect on the observed amplitudes and hence on the final value of bias (Marshall, personal communication). The bias between any two test sites should be a sum of these effects. Murphy and Tzeng (1982) estimated the bias by comparing signals recorded near NTS and Semipalatinsk from Aleutian Islands earthquakes. They estimated the bias as 0.24 magnitude unit. Priestley *et al.* (1987) used a similar approach, and they estimated the bias as 0.34. It should be noted, however, that all these earlier bias estimates were made before the publication of Bocharov *et al.* (1989) and Vergino (1989).

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APPENDIX

GEOTECH'S MAXIMUM-LIKELIHOOD NETWORK m_b: GLM90A

Short-period WWSSN vertical recordings (SPZ) of body waves from 96 nuclear explosions detonated at the Semipalatinsk Test Site, Eastern Kazakhstan, USSR, are being measured and added to our database to determine the optimal network magnitudes using the maximum-likelihood estimator (MLE), which accounts for the effects of data censoring due to clipping and to noise.[1,2] As of now, our WWSSN database has been expanded to 124 events (totaling 366 usable "a", "b", and "max" event phases) from a variety of test sites. Only the stations at teleseismic distance (20 to 95 degrees) were used in the network m_b determination. (Therefore, some of the m_b values might be slightly different from those in an earlier report TGAL-87-05.) The 8501 good signals, 5699 noise measurements, and 1088 clipped recordings yield a $\hat{\sigma}_{MLE}$ 0.320.

The 124 events in Table A1 are grouped by test sites. The three numbers under the column "# of signals" represent the number of signals, noise, and clips associated with the P_{max} phase of each event. Except for the U.S. and French Sahara explosions which have specific code names, all the remaining events are identified with the dates and abbreviated test site codes shown below:

azg	Azgir, U.S.S.R.
pne	"PNE", Urals, U.S.S.R.
mek	Murzhik (Konystan), E. Kazakh, U.S.S.R.
dek	Degelen Mountain, E. Kazakh, U.S.S.R.
sek	Shagan River (Balapan), E. Kazakh, U.S.S.R.
nnz	Northern Novaya Zemlya, U.S.S.R.
snz	Southern Novaya Zemlya, U.S.S.R.
tu	Tuamoto Islands, France
raj	Rajasthan, India
ch	Lop Nor, Sinkiang, China

Table A2 lists the station correction terms determined jointly along with the network m_b values.

[1] Blandford, R. R., and R. H. Shumway (1982). Magnitude:yield for nuclear explosions in granite at the Nevada Test Site and Algeria: joint determination with station effects and with data containing clipped and low-amplitude signals, *Technical Report VSC-TR-82-12*, Teledyne Geotech, Alexandria, Virginia.

[2] Jih, R.-S., and R. H. Shumway (1989). Iterative network magnitude estimation and uncertainty assessment with noisy and clipped data, *Bull. Seismo. Soc. Am.*, 79, 1122-1141.

Table A1. Geotech's Maximum-Likelihood Network m_b					
Event	# of Signals	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$	σ
ALMENDRO	26,0,2	5.730	6.026	6.233	0.060
BENHAM	42,1,7	5.772	6.103	6.359	0.045
BILBY	36,3,0	5.148	5.404	5.658	0.051
BOURBON	18,31,0	4.587	4.720	4.904	0.046
BOXCAR	32,0,4	5.849	6.189	6.412	0.053
CAMBRIC	12,34,0	4.091	4.340	4.551	0.047
CHANCELLOR	16,12,1	4.887	5.183	5.338	0.059
CHARTREUSE	31,16,1	4.884	5.010	5.249	0.046
CHATEAUGAY	17,28,2	4.478	4.884	5.066	0.047
CORDUROY	18,14,0	4.971	5.092	5.287	0.057
HANDCAR	16,33,0	4.308	4.495	4.629	0.046
HANDLEY	41,1,1	6.062	6.307	6.480	0.049
HARZER	31,5,1	5.011	5.312	5.536	0.053
KANKAKEE	24,27,0	4.347	4.597	4.847	0.045
MAST	29,1,0	5.403	5.739	5.981	0.058
NASH	31,21,0	4.758	4.918	5.149	0.044
PILEDRIVER	38,12,1	4.925	5.194	5.435	0.045
REX	16,35,1	3.875	4.376	4.720	0.044
SCOTCH	38,8,1	5.079	5.344	5.600	0.047
CANNIKIN	49,0,20	6.408	6.663	6.911	0.039
MILROW	52,0,4	5.945	6.195	6.494	0.043
LONGSHOT	67,4,3	5.056	5.428	5.818	0.037
FAULTLESS	47,1,3	5.829	6.157	6.460	0.045
GASBUGGY	11,37,0	4.153	4.412	4.661	0.046
RIO BLANCO	15,20,0	4.068	4.545	4.810	0.054
RULISON	9,37,0	4.108	4.240	4.554	0.047
SHOAL	13,27,0	4.321	4.455	4.738	0.051
SALMON	6,33,0	3.439	3.974	4.180	0.051

Table A1. Geotech's Maximum-Likelihood Network m_b (Continued)					
Event	# of Signals	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$	σ
azg22apr66	3,10,0	3.867	4.101	4.183	0.089
azg22dec71	12,0,2	5.473	5.826	6.164	0.086
azg25apr75	1,16,0	___	3.904	3.944	0.078
azg29jul76	41,5,7	5.105	5.579	5.864	0.044
azg30sep77	21,30,1	4.049	4.588	4.828	0.044
azg17oct78	7,0,5	5.271	5.724	6.097	0.092
azg18dec78	9,0,3	5.374	5.748	6.119	0.092
azg17jan79	10,0,4	5.515	5.869	6.153	0.086
azg14jul79	10,0,1	4.831	5.371	5.699	0.097
azg24oct79	3,0,6	4.848	5.681	5.960	0.107
pne29aug74	27,18,0	3.994	4.397	4.722	0.048
mek18dec66	55,9,1	5.261	5.493	5.709	0.040
dek21nov65	48,15,1	4.875	5.152	5.362	0.040
dek13feb66	51,4,10	5.640	5.890	6.082	0.040
dek20mar66	50,9,8	5.335	5.624	5.850	0.039
dek07may66	9,26,1	3.992	4.233	4.486	0.053
dek26feb67	48,9,6	5.353	5.597	5.821	0.040
dek29sep68	50,8,6	5.125	5.432	5.627	0.040
dek23jul69	38,21,1	4.594	4.920	5.167	0.041
dek11sep69	19,39,0	3.975	4.234	4.576	0.042
dek25apr71	37,5,0	5.299	5.566	5.756	0.049
dek30dec71	16,3,0	4.982	5.347	5.524	0.073
dek28mar72	28,17,0	4.351	4.726	4.959	0.048
dek16aug72	24,23,1	4.337	4.620	4.885	0.046
dek10dec72	30,7,5	4.975	5.333	5.532	0.049
dek29mar77	25,14,0	4.304	4.700	4.981	0.051
dek30jul77	21,16,0	4.200	4.604	4.857	0.053
dek26mar78	25,6,0	4.948	5.272	5.497	0.057
dek22apr78	21,9,0	4.466	4.765	5.014	0.058

Table A1. Geotech's Maximum-Likelihood Network m_b (Continued)					
Event	# of Signals	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$	σ
sek15jan65	46,1,2	5.493	5.732	5.880	0.046
sek19jun68	28,3,2	4.618	5.000	5.261	0.056
sek30nov69	32,0,0	5.378	5.767	5.975	0.057
sek30juh71	31,19,1	4.470	4.766	5.038	0.045
sek10feb72	34,8,2	4.803	5.071	5.304	0.048
sek02nov72	29,1,15	5.590	5.938	6.187	0.048
sek10dec72	29,2,11	—	5.784	6.013	0.049
sek23jul73	38,1,1	5.753	5.996	6.181	0.051
sek14dec73	45,8,6	5.245	5.545	5.770	0.042
sek27apr75	18,1,1	4.904	5.242	5.491	0.072
sek04jul76	14,0,5	5.229	5.598	5.927	0.073
sek07dec76	17,2,1	4.961	5.416	5.606	0.072
sek11jun78	17,0,1	5.296	5.580	5.889	0.075
sek15sep78	30,1,5	5.431	5.691	5.884	0.053
sek23jun79	38,3,3	5.615	5.846	6.049	0.048
sek14sep80	29,5,6	5.439	5.752	5.987	0.051
nnz27oct66	56,0,14	6.063	6.295	6.436	0.038
nnz21oct67	53,5,3	5.400	5.590	5.765	0.041
nnz07nov68	59,1,5	5.580	5.831	6.025	0.040
nnz14oct69	59,2,7	5.760	5.957	6.129	0.039
nnz14oct70	35,0,22	6.424	6.633	6.813	0.042
nnz27sep71	23,0,21	6.259	6.475	6.619	0.048
nnz28aug72	32,0,11	5.989	6.247	6.371	0.049
nnz12sep73	23,0,21	6.347	6.672	6.763	0.048
nnz29aug74	25,0,18	6.126	6.394	6.578	0.049
nnz21oct75	23,0,17	6.095	6.333	6.541	0.051
nnz23aug75	28,0,12	6.112	6.367	6.488	0.051
nnz20oct76	25,34,1	4.031	4.350	4.659	0.041
nnz01sep77	26,2,2	5.099	5.415	5.561	0.058
nnz10aug78	39,3,18	5.392	5.625	5.856	0.041

Table A1. Geotech's Maximum-Likelihood Network m_b (Continued)					
Event	# of Signals	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$	σ
nnz11oct80	42,4,6	5.181	5.442	5.658	0.044
nnz01oct81	43,4,5	5.226	5.489	5.649	0.044
nnz18aug83	30,5,5	5.321	5.526	5.703	0.051
nnz25oct84	22,3,4	5.154	5.427	5.599	0.059
snz27sep73	32,3,1	5.196	5.490	5.729	0.053
snz27oc73a	14,0,24	6.647	6.873	7.092	0.052
snz27oc73b	9,28,0	—	3.999	4.150	0.053
snz27oc73c	4,34,0	3.544	3.886	3.908	0.052
snz02nov74	12,0,29	6.497	6.790	7.012	0.050
snz18oct75	21,0,21	6.227	6.518	6.834	0.049
BERYL	11,6,0	4.412	4.778	4.985	0.078
CORUNDON	11,42,0	3.797	3.899	4.212	0.044
EMERAUDE	14,25,0	—	4.261	4.566	0.051
GRENAT	32,32,1	4.292	4.494	4.763	0.040
OPALE	3,51,0	3.770	3.855	3.896	0.044
RUBIS	42,5,0	4.826	5.167	5.429	0.047
SAPHIR	52,5,5	5.182	5.464	5.716	0.041
TOURMALINE	27,39,0	4.106	4.427	4.644	0.039
TURQOISE	11,55,0	—	3.941	4.221	0.039
tu19feb77	16,28,0	—	4.370	4.622	0.048
tu19mar77	20,6,1	5.141	5.438	5.639	0.062
tu24nov77	33,0,0	5.051	5.369	5.662	0.056
tu25jul79	18,0,0	5.090	5.570	5.864	0.075
tu23mar80	27,14,3	4.677	5.105	5.358	0.048
tu19jul80	38,2,2	4.891	5.158	5.513	0.049
tu03dec80	32,11,0	4.689	4.981	5.331	0.049
tu25jul82	22,13,0	4.675	5.034	5.210	0.054
tu19apr83	22,1,0	4.993	5.199	5.495	0.067

Table A1. Geotech's Maximum-Likelihood Network m_b (Continued)					
Event	# of Signals	$m_b(P_a)$	$m_b(P_b)$	$m_b(P_{max})$	σ
tu25may83	18,0,0	5.150	5.455	5.785	0.075
tu30nov78	40,7,2	4.820	5.234	5.611	0.046
raj18may74	7,23,0	4.022	4.303	4.563	0.058
ch22sep69	30,12,0	4.325	4.742	5.133	0.049
ch27oct75	12,24,0	4.131	4.396	4.585	0.053
ch17oct76	13,33,0	3.884	4.146	4.532	0.047
ch06oct83	17,13,1	4.769	5.029	5.243	0.057
ch03oct84	10,12,0	4.453	4.747	4.999	0.068
ch19dec84	3,10,0	4.017	3.999	4.381	0.089

Table A2. WWSSN Station Corrections					
Code	# of Signals	Site Term	Longitude	Latitude	Description
AAE	78,93,17	-0.243±0.023	38.765556	9.029166	Addis Ababa, Ethiopia
AAM	134,64,6	0.254±0.022	-83.656113	42.299721	Ann Arbor, Michigan
ADE	16,25,0	0.001±0.050	138.708893	-34.966946	Adelaide, Australia
AFI	27,65,0	-0.143±0.033	-171.777252	-13.909333	Afiamalu, Samoa Islands
AKU	71,69,0	-0.093±0.027	-18.106667	65.686668	Akureyri, Iceland
ALQ	99,15,19	0.039±0.028	-106.457497	34.942501	Albuquerque, New Mexico
ANP	20,67,0	-0.327±0.034	121.516670	25.183332	Anpu, Formosa
ANT	41,49,2	0.056±0.033	-70.415276	-23.705000	Antofagasta, Chile
AQU	66,44,13	-0.054±0.029	13.403055	42.353889	Aquila, Italy
ARE	83,40,0	0.101±0.029	-71.491280	-16.462084	Arequipa, Peru
ASP	1,2,0	-0.581±0.185	133.896667	-23.683332	Alice Springs, Australia
ATL	79,19,2	0.164±0.032	-84.337502	33.433334	Atlanta, Georgia
ATU	112,78,16	0.146±0.022	23.716667	37.972221	Athens Univ., Greece
BAG	132,68,8	-0.028±0.022	120.579720	16.410833	Baguio City, Philippine Islands
BDF	10,2,0	-0.009±0.092	-47.903332	-15.663834	Brasilia array, Brazil
BEC	45,102,3	-0.131±0.026	-64.681114	32.379444	Bermuda-Columbia, Atlantic Ocean
BHP	30,75,0	-0.176±0.031	-79.558052	8.960834	Balboa Heights, Panama
BKS	141,65,1	0.087±0.022	-122.235001	37.876667	Byerly, California
BLA	152,53,12	0.122±0.022	-80.420998	37.211304	Blacksburg, West Virginia
BOG	41,76,0	0.057±0.030	-74.065002	4.623055	Bogota, Colombia
BOZ	44,4,5	0.238±0.044	-111.633331	45.599998	Bozeman, Montana
BUL	149,34,9	0.049±0.023	28.613333	-20.143333	Bulawayo, Rhodesia
CAR	92,59,7	0.154±0.025	-66.927635	10.506667	Caracas, Venezuela
CCG	1,0,0	-0.186±0.320	-61.133335	77.166664	Camp Century, Greenland
CHG	97,16,36	-0.127±0.026	98.976944	18.790001	Chiengmai, Asia
CMC	50,27,0	-0.140±0.036	-115.083336	67.833336	Copper Mine, Canada
COL	259,47,28	0.087±0.018	-147.793335	64.900002	College Outposta, Alaska
COP	74,101,14	0.166±0.023	12.433333	55.683334	Copenhagen, Denmark
COR	77,59,3	0.111±0.027	-123.303192	44.585724	Corvallis, Oregon
CTA	57,16,4	0.214±0.036	146.254440	-20.088333	Charters Towers, Australia

Table A2. WWSSN Station Corrections (Continued)					
Code	# of Signals	Site Term	Longitude	Latitude	Description
DAG	21,13,5	0.001±0.051	-18.770000	76.769997	Danmarkshavn, Greenland
DAL	17,24,4	0.191±0.048	-96.783890	32.846111	Dallas, Texas
DAV	24,81,0	-0.276±0.031	125.574722	7.087778	Davao, Philippine Islands
DUG	170,17,29	0.075±0.022	-112.813332	40.195000	Dugway, Utah
EIL	25,3,43	0.075±0.038	34.950001	29.549999	Eilat, United Arab Republic
EPT	29,2,2	0.005±0.056	-106.505836	31.771667	El Paso, Texas-Mexico border
ESK	88,80,2	0.117±0.025	-3.205000	55.316666	Eskdalemuir, United Kingdom
FLO	80,20,9	0.064±0.031	-90.370003	38.801666	Florissant, Missouri
FVM	44,8,0	-0.008±0.044	-90.426003	37.984001	French Village, Missouri
GDH	154,126,1	-0.159±0.019	-53.533333	69.250000	Godhavn, Greenland
GEO	88,69,2	0.021±0.025	-77.066666	38.900002	Georgetown, Virginia
GIE	9,38,0	-0.188±0.047	-90.300003	-0.733333	Galapagos Islands
GOL	157,24,11	-0.216±0.023	-105.371109	39.700279	Golden, Colorado
GRM	1,20,0	-0.093±0.070	26.573334	-33.313332	Grahamstown, South Africa
GSC	89,22,16	0.089±0.028	-116.804611	35.301666	Goldstone, California
GUA	78,175,0	-0.250±0.020	144.911667	13.538333	Guam, Mariana Islands
HKC	85,84,0	-0.131±0.025	114.171890	22.303556	Hong Kong
HLW	47,36,32	-0.047±0.030	31.341667	29.858334	Helwan, United Arab Republic
HNR	30,92,0	0.188±0.029	159.947113	-9.432195	Honiara, Solomon Islands
HON	6,9,0	0.051±0.083	-158.008331	21.321667	Honolulu, Hawaii
HOW	1,10,0	0.258±0.097	88.309166	22.416666	Howrah, India-Bangladesh border
IST	102,79,25	0.186±0.022	28.995832	41.045555	Istanbul, Turkey
JCT	59,4,24	0.159±0.034	-99.802223	30.479445	Junction City, Texas
JER	89,45,25	0.039±0.025	35.197224	31.771944	Jerusalem, Dead Sea
KBL	14,0,46	0.142±0.041	69.043167	34.540833	Kabul, Afghanistan
KBS	55,40,0	-0.181±0.033	11.923889	78.917503	Kingsbay, Svalbard
KEV	121,102,4	-0.123±0.021	27.006666	69.755280	Kevo, Finland
KIP	84,153,0	0.107±0.021	-158.014999	21.423334	Kipapa, Hawaii
KOD	107,33,30	0.100±0.025	77.466667	10.233334	Kodaikanal, India
KON	129,65,70	0.102±0.020	9.598222	59.649082	Kongsberg, Norway

Table A2. WWSSN Station Corrections (Continued)					
Code	# of Signals	Site Term	Longitude	Latitude	Description
KRK	8,7,0	-0.171±0.083	30.062500	69.724167	Kirkenes, Norway-USSR border
KTG	72,75,1	-0.247±0.026	-21.983334	70.416664	Kap Tobin, Greenland
LAH	5,17,3	0.428±0.064	74.333336	31.549999	Lahore, India-Pakistan border
LEM	54,82,0	-0.531±0.027	107.616669	-6.833333	Lembang, Java
LON	162,44,21	-0.034±0.021	-121.809998	46.750000	Longmire, Washington
LOR	74,8,16	0.154±0.032	3.851389	47.266666	Lormes, France
LPA	8,91,0	0.426±0.032	-57.931946	-34.908890	La Plata, Uruguay
LPB	58,39,3	-0.043±0.032	-68.098358	-16.532667	La Paz, Peru-Bolivia border
LPS	50,27,3	-0.071±0.036	-89.161942	14.292222	La Palma, Quatemala
LUB	40,30,3	0.214±0.037	-101.866669	33.583332	Lubbock, Texas
MAL	87,41,10	0.055±0.027	-4.411111	36.727501	Malaga, straits of Gibraltar
MAN	30,14,1	0.316±0.048	121.076859	14.662000	Manila, Philippine Islands
MAT	145,53,25	-0.112±0.021	138.206665	36.541668	Matsushiro, Japan
MDS	39,19,0	-0.032±0.042	-89.760002	43.372223	Madison, Wisconsin
MHI	5,2,2	0.358±0.107	59.494499	36.299999	Meshed, Iran-USSR border
MNN	8,6,2	0.179±0.080	-93.190002	44.914444	Minneapolis, Minnesota
MSH	31,19,9	0.226±0.042	59.587776	36.311111	Meshed, Iran-USSR border
MSO	46,7,2	0.061±0.043	-113.940552	46.829166	Missoula, Montana
MUN	39,41,0	0.015±0.036	116.208336	-31.978333	Mundaring, Australia
NAI	115,46,9	-0.089±0.025	36.803665	-1.273944	Nairobi, Kenya
NAT	27,27,0	0.070±0.044	-35.033333	-5.116667	Natal, Brazil
NDI	129,24,25	0.124±0.024	77.216667	28.683332	New Delhi, India
NHA	12,3,0	-0.127±0.083	109.211670	12.210000	Nhatranga, Asia
NIL	14,6,18	-0.008±0.052	73.251663	33.650002	Nilore, Pakistan
NNA	47,57,0	-0.162±0.031	-76.842140	-11.987556	Nana, Peru
NOR	78,50,3	-0.260±0.028	-16.683332	81.599998	Nord, Greenland
NUR	103,82,7	0.051±0.023	24.651417	60.508999	Nurmijarvi, Finland
OGD	135,63,6	-0.119±0.022	-74.595833	41.087502	Ogdensburg, New York
OXF	79,10,17	0.347±0.031	-89.409164	34.511806	Oxford, Mississippi
PDA	31,103,3	0.050±0.027	-25.663334	37.746666	Ponta Delgada, Azores Islands

Table A2. WWSSN Station Corrections (Continued)					
Code	# of Signals	Site Term	Longitude	Latitude	Description
PEL	29,39,3	0.052±0.038	-70.685280	-33.143612	Peldehue, Chile-Argentina
PMG	82,58,2	-0.005±0.027	147.153885	-9.409166	Port Moresby, New Guinea
POO	133,40,28	0.037±0.023	73.849998	18.533333	Pcona, India
PRE	65,42,0	-0.074±0.031	28.190001	-25.753334	Pretoria, South Africa
PTO	84,52,5	-0.140±0.027	-8.602222	41.138611	Porto Serro Do, Portugal
QUE	82,23,41	-0.412±0.026	66.949997	30.188334	Quetta, Pakistan
QUI	9,67,0	0.007±0.037	-78.500504	-0.200139	Quito, Ecuador
RAB	45,135,0	-0.177±0.024	152.169830	-4.191278	Rabaul, New Britain
RAR	12,30,0	-0.070±0.049	-159.773331	-21.212500	Rarotonga, Cook Islands
RCD	28,22,3	0.439±0.044	-103.208336	44.075001	Rapid City, South Dakota
RIV	9,22,0	0.355±0.057	151.158340	-33.829361	Riverview, Australia
SBA	2,12,0	-0.619±0.086	166.756104	-77.850281	Scott Base, Antarctica
SCP	167,68,21	0.055±0.020	-77.864998	40.794998	State College, Pennsylvania
SDB	75,17,9	0.083±0.032	13.571944	-14.925834	Sa Da Bandeira, Angola
SEO	97,76,12	-0.076±0.024	126.966667	37.566666	Seoul Keizyo, South Korea
SHA	76,65,0	0.346±0.027	-88.142807	30.694361	Spring Hill, Mississippi
SHI	77,14,30	0.298±0.029	52.519943	29.638306	Shiraz, Iran
SHK	41,76,0	-0.324±0.030	132.677505	34.532223	Shiraki, Honshu, Japan
SHL	83,15,41	0.033±0.027	91.883331	25.566668	Shillong, India-Bangladesh border
SJG	129,57,0	-0.248±0.023	-66.150002	18.111666	San Juan, Puerto Rico
SNA	6,11,0	0.108±0.078	-2.325000	-70.315002	Sanae, Antarctica
SNG	44,31,3	-0.072±0.036	100.620003	7.173333	Songkhla, Malay Peninsula
SPA	13,7,0	-0.756±0.072	0.000000	-90.000000	South Pole, Antarctica
STU	172,94,20	0.094±0.019	9.195000	48.771946	Stuttgart, Germany
TAB	76,53,5	0.216±0.028	46.326668	38.067501	Tabriz, Iran-USSR border
TAU	12,14,0	-0.115±0.063	147.320419	-42.909916	Tasmania Univ., Tasmania
TOL	112,52,23	0.211±0.023	-4.048611	39.881390	Toledo, Spain
TRI	128,85,25	-0.105±0.021	13.764167	45.708889	Trieste, Italy
TRN	112,70,1	0.101±0.024	-61.402779	10.648916	Trinidad, Trinidad
TUC	57,3,21	0.077±0.036	-110.782219	32.309723	Tucson, Arizona

Table A2. WWSSN Station Corrections (Continued)					
Code	# of Signals	Site Term	Longitude	Latitude	Description
UME	123,53,2	0.170±0.024	20.236666	63.814999	Umea, Sweden
UNM	10,13,1	-0.236±0.065	-99.178085	19.329000	Nat. University of Central Mexico
UPA	2,1,0	-0.261±0.185	-79.533997	8.981500	Univ. de Panama, Panama
VAL	122,122,12	0.015±0.020	-10.244166	51.939445	Valentia Eire
WEL	8,12,0	0.139±0.072	174.768326	-41.286110	Wellington, New Zealand
WES	135,118,6	-0.139±0.020	-71.322083	42.384693	Weston, New England
WIN	32,29,0	-0.186±0.041	17.100000	-22.566668	Windhoek, South-West Africa

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